DEVELOPMENT OF A PAVEMENT LIFE CYCLE ASSESSMENT TOOL FOR AIRFIELD REHABILITATION STRATEGIES

BY

JOHN M. KULIKOWSKI

THESIS

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Adviser:

Professor Jeffery R. Roesler

ABSTRACT

The demand to provide more sustainable facilities and infrastructure has increased over the past ten years. The ability to measure and quantify the environmental impacts of infrastructure projects like life cycle costs is in higher demand. Life cycle assessment (LCA) studies/tools are developed for highway infrastructure and pavements with a limited number of studies developed for airports and even fewer for the airport pavement infrastructure. A pavement LCA tool called LCA-AIR 1.0 is introduced to fill the necessary gap in quantifying sustainability strategies for airfield pavements. LCA-AIR incorporates the material production, construction/maintenance and rehabilitation, and use phases in the analysis. Standard indicators from TRACI are used to quantify these impacts based on two functional units (square yard and pounds-mile traveled). To assess and evaluate the viable rehabilitation strategies, comprehensive and accurate field data must be collected. A summary of LIDAR and laser scanning technology and projects for highway and airport infrastructure is presented. An LCA case study was performed for three candidate rehabilitation strategies on Taxiway A and B at O'Hare International Airport in Chicago, IL: rubblization with mill/asphalt inlay, precast concrete panel replacement, and full depth reconstruction of existing concrete pavement structure. An extensive literature review and investigation into the use of precast concrete pavement on airports in the US and abroad is documented for application to rapid rehabilitation. LCA-AIR showed that each phase contributed at different magnitudes to the environmental impact with the use phase producing the greatest LCA impact factors. The LCA analysis focused on the construction/maintenance and rehabilitation (CMR) phase, as the material production (MP) phase for initial construction and use (U) phase were the same for all cases. The GWP potential for PCP was 2,395 kg CO_2/yd^2 (4.700×10^{-10} kg CO_2/lb-mile), for rubblization was 2,395 kg CO_2/yd^2 (4.310×10^{-10} kg CO_2/lb-mile), and for reconstruction was 2,395 kg CO_2/yd^2 (4.701×10^{-10} kg CO_2/lb-mile). The energy consumed for rubblization was 0.18612 TJ/ yd^2 (3.576×10^{-8} TJ/lb-mile), for PCP was 0.18617 TJ/ yd^2 (3.654×10^{-8} TJ/lb-mile) and for reconstruction was 0.18628 TJ/ yd^2 (3.656×10^{-8} TJ/lb-mile).

To My Incredible Wife, Shaylee and My Amazing Children – I love you!

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DISCLAIMER

The views expressed in this thesis are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government.

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ACRONYMS

AC – Asphalt Concrete Pavement
AFRL – Air Force Research Laboratory
ATADS – Air Traffic Activity System
CMP – Common Midpoint
CMR – Construction, Maintenance and Rehabilitation
DMI – Distance Measurement Indicators
ERDC – US Army Engineer Research and Development Center
FHWA – Federal Highway Administration
FOD – Foreign Object Debris
GNSS – Global Navigation Satellite System
GPR – Ground Penetrating Radar
GPS – Global Positioning System
GWP – Global Warming Potential
HWD – Heavy Weight Deflectometer
JPCP – Jointed Plain Concrete Pavements
JRCP – Jointed Reinforced Concrete Pavement
LCA – Life Cycle Assessment
LIDAR – Light Detection and Ranging
LTE – Load Transfer Efficiency
LTTP – Long Term Pavement Performance
MP – Material Production
MTOW – Maximum Takeoff Weight
NCHRP – National Cooperative Highway Research Program
NGS – National Geodetic Survey
ORD – Chicago O'Hare International Airport
PCASE – Pavement-Transportation Computer Assisted Structural Engineering
PCC – Portland Cement Concrete Pavement
PCI – Pavement Condition Index
PCP – Precast Concrete Pavement
PPCP – Precast, Prestressed Concrete Pavement
PPS – Precast Pavement Systems
PRC – Precast Reinforced Concrete Pavements (Japan)
RW – Runway
TW – Taxiway
UAV – Unmanned Aerial Vehicle
U – Use Phase
UIUC – University of Illinois at Urban-Champaign

CHAPTER 1 - INTRODUCTION OF LIFE CYCLE ASSESSMENT

1.1 Motivation for Airfields

In the United States the transportation sector generates 27% of total US greenhouse gas emissions (GHG) of which, aircraft account for 8.2% of the total (Federal Highway Administration, 2015). The US has an estimated 15,000 airports. Airports world-wide (U.S.) process 3.3 billion passengers (838 million), 3.6 trillion passenger-miles (963 billion) and 55 million short-tons of freight annually driving, approximately 3.0% of the worlds GDP (International Civil Aviation Organization, 2014; Senguttuvan, 2011). Although the infrastructure quantity and areas are smaller than roadways, airports still have a significant environmental impact. In order to identify opportunities to reduce the environmental impacts of airport pavements, an LCA framework is required to first quantify the energy consumption and impact factors of current practices and operations.

The ability to measure and quantify the environmental impacts of infrastructure and facilities is vital. Fowler and Rauch (2006) provide a thorough review of facility rating systems such as LEED, Green Globes, Green Star, GBTool, CASBEE, BREEAM, etc. Multi-disciplinary infrastructure projects use rating systems such as ENVISION to measure sustainability on a more comprehensive level (Institute for Sustainable Infrastructure & Zofnass Program for Sustainable Infrastructure, 2015). More specific to transportation infrastructure and pavement facilities are rating systems such as Green Roads, INVEST, Illinois Tollway LCA Tool, etc. These rating systems help transportation agencies and other organizations find sustainable and innovative solutions to minimize their impacts on the environment. Currently, airport pavements do not have such rating systems. The Chicago Department of Aviation uses a *Sustainable Airport Manual* to guide project efforts to minimize environmental impacts for building facilities, maintenance materials, and parking areas (Chicago Department of Aviation, 2013). This living document has evolved since introduction in 2003 and is based on the LEED rating system but this manual does not provide considerations for airfield pavements.

Project rating systems attribute points to specific actions taken during the design, construction, maintenance and operation of the facility but they do not quantify the environmental impacts resulting from the sustainability choices for a particular project. A life cycle assessment (LCA) is a method to quantify these environmental impacts from processes and projects throughout its life (Santero N. J., 2009). LCA studies/tools have been completed and developed for highway pavements, such as Athena Pavements LCA (Athena Sustainable Materials Insitute, 2013), the Illinois Tollway tool, ICT-LCA (Al-Qadi, et al., 2015), PaLate (Horvath, 2004), and PE-2 (Mukherjee & Cass, 2011). Similar LCA studies and tools are needed for airport pavements. This thesis presents the methodology and development of an airport pavement LCA tool called LCA-AIR. The initial development of LCA-AIR quantifies the environmental impacts of airfield pavement using the Tool for the Reduction and Assessment of Chemical and other Environmental Impacts 2.1 (TRACI) categories established by the Environmental Protection Agency (EPA) (U.S. Environmental Protection Agency, 2012). LCA-AIR can be used by airport owners, operators and engineers in their decision making process to make sustainable pavement choices based on quantitative comparisons.

1.2 Research Objectives

The research objectives are:

1. To develop a generalized airfield pavement LCA tool
2. To describe the viability of precast concrete pavement (PCP) use in highways and airports for rehabilitation
3. To determine the environmental impacts of three maintenance/rehabilitation cases using a LCA approach for Taxiway A & B at O'Hare International Airport.

Chapter 1 discusses the principles of LCA. Chapter 2 discusses the methodology and development of the LCA tool – LCA-AIR. It also contains a case study of its use for the construction of a full depth AC and PCC airfield pavement. Chapter 3 provides a background and current state of Taxiway A & B located at O'Hare International Airport in Chicago, IL. Based on initial testing and evaluation, multiple rehabilitation strategies were determined for additional analysis Chapter 4 provides an in depth discussion of precast concrete panels, the available systems, and their application in highways and airports. Chapter 5 is the LCA for three rehabilitation strategies; rubblization with a mill/AC inlay, precast panels, and reconstruction. Chapter 6 provides a literature review on the use of LIDAR and laser scanning techniques for airfields in order to provide a more comprehensive topographic and condition assessment than traditional, manual pavement surveys for future investment decisions.

1.3 Life Cycle Assessment Tool Framework

LCAs can consider the entire lifespan or a limited number of phases of a product, service or system with LCAs often completed to compare multiple products, services or systems. To ensure consistency in LCAs, the International Organization for Standardization (ISO) created two standards in 2006: ISO 14040:2006 and 14044:2006 (International Organization for Standardization, 2006) with additional technical reports published to assist in application of the standards (International Organization for Standardization, 2012). Other countries or regions have also published LCA standards such as PAS 2050:2011 by the British Standards Institute or EN 15804:2012 by the European Standard. ISO 14040 defines the four, high-level framework components of an LCA as seen below in Figure 1.

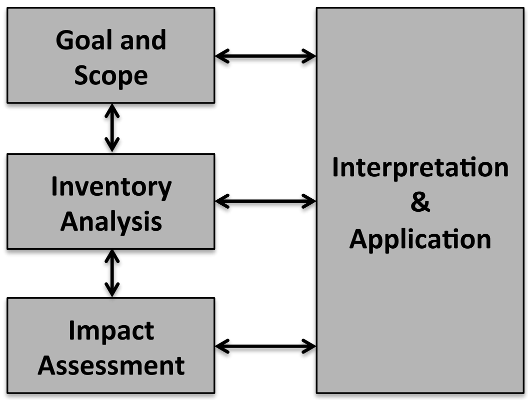


Figure 1 - LCA Framework (adapted from ISO 14040)

The goal and scope includes the intended application and audience. The scope describes the boundaries, assumptions/limitations and the methodology for the assessment. Critical items in the scope are the functional unit, system boundaries, impact categories, allocation procedures, and data quality. The inventory analysis is critical and the most time consuming component. Balance must be struck on the analysis based on time to completion, available money, and data (quantity and quality). During this step, data is collected and analyzed in accordance with the goal and scope. The inventory data and sources determine the quality of the LCA. The inputs and outputs are assembled into a life cycle inventory (LCI) for each process defined in the project scope. Data used in the LCA can be primary and/or secondary. Primary data is collected at the source for each process in the product, service, or system. Secondary data is generic industry averages, which may come from databases or literature. Data quality is measured using indicators such as, technology (compatibility of technology at data collection time), time (age of data), geography (location of data sources), completeness (adequate period to even out normal fluctuations) and reliability (verifiability of measurements).

The impact assessment characterizes the inventory results into indicators (e.g. global warming potential, ecotoxicity, resource depletion, etc.) as defined in the goal and scope. These impacts are then related to the specific engineering field. The interpretation includes the evaluation of information and results from the previous steps to analyze content, develop conclusions, assess limitations and formulate recommendations (Lewis, 2013). As seen in Figure 1, the arrows are bi-directional, which depicts the iterative process of a LCA. The LCA can be refined at each step to ensure consistency and quality of the final product.

CHAPTER 2 – DEVELOPMENT OF LCA-AIR – AN AIRPORT LIFE CYCLE ASSESSMENT TOOL

This chapter discussed the development of a LCA tool: LCA-AIR. It also demonstrates the tools capabilities by analyzing the construction of a PCC and AC pavement structure using virgin materials and recycled materials.

2.1 LCA-AIR Development Methodology

A standard airport configuration [runway (RW), parallel taxiway (TW), ladder TWs and apron] was selected for the initial tool development as seen in Figure 2. This airport configuration serves as the basis for all processes considered in developing such an airport tool. Currently the LCA tool is limited to analysis of two runways, four taxiways and two aprons. Excel is used to provide the interface and database for this tool. Functional unit, system boundaries, impact categories, data quality and collection, and assumptions need to be stated to meet established standards. These are discussed briefly in the following sections.

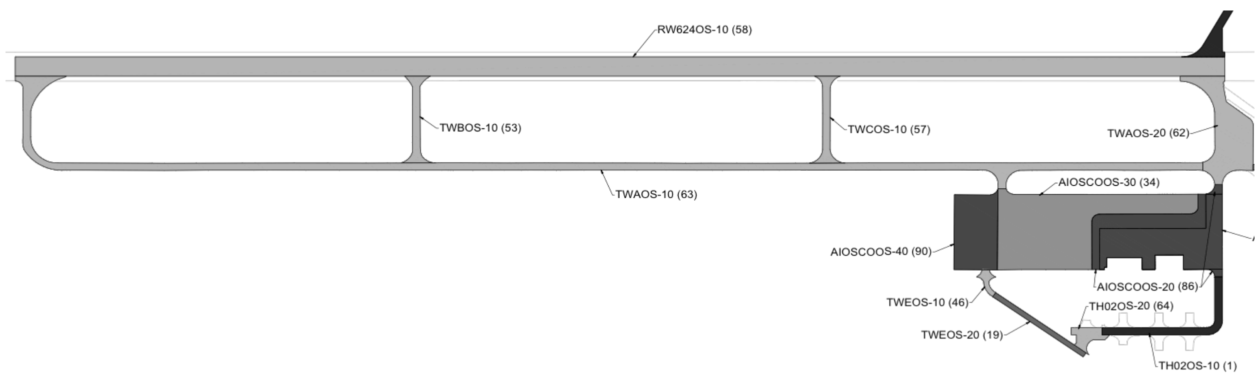


Figure 2 - Standard Airport Configuration

2.1.1 Functional Unit

The functional unit serves as the base unit to which the results are normalized. The function of an airfield is to provide operating space for aircraft in moving goods and passengers over its design life. Due to complexity of airports, two functional units were used. The first is square yards for all the processes except airplane operations. The second functional unit for aircraft operation is pound-mile traveled.

2.1.2 System Boundaries

The system boundary defines what processes, materials, and systems are included or excluded from the study. The system boundary in this study includes all the traditional life cycle phases of the pavement except the end of life phase. The system boundaries are consistent with LCA pavement frameworks published previously (Santos, et al., 2014; University of California Pavement Research Center, 2010). Industry practice is to recycle the pavement materials at end of life. Due to the complexity of airports, their growth and land planning strategy, uncertainty exists for the pavement's final state and thus, recycling of pavement layer materials at end of life was currently not assumed. For highways, Santero et al. noted similar complexities in end of life and recycling allocations (Santero et al., 2011). A traditional highway LCA considers vehicle operations (fuel consumption) and not manufacturing, maintenance and disposal impacts. Similarly, LCA-AIR only considers flight operation for aircraft. Upstream impacts from aircraft manufacturing, facility construction and downstream impacts from aircraft maintenance and disposal were not included. Figure 3 below, shows the system boundary used in this study.

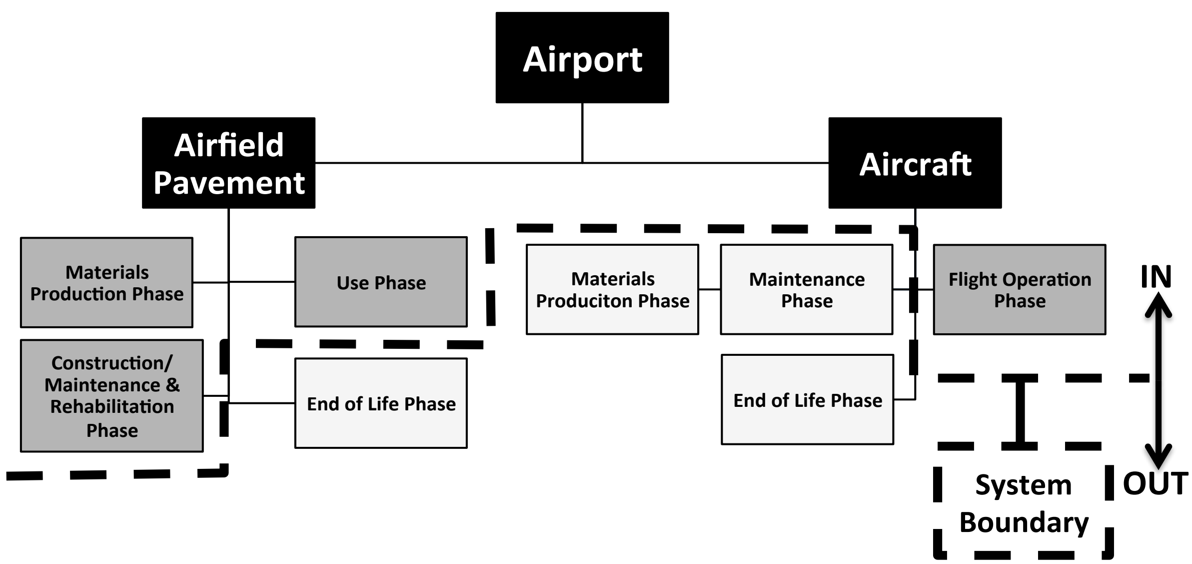


Figure 3 - System Boundary for LCA-AIR

2.1.3 Impact Categories

Impact categories are the metrics used to evaluate the impacts from different processes, materials, and systems. The TRACI and primary energy consumption impacts, with the units used in this LCA, are shown in Table 1.

Table 1 - TRACI Environmental and Energy Impacts

Impact category	Unit
Ozone depletion	kg CFC-11 eq
Global warming potential	kg CO2 eq
Smog	kg O3 eq
Acidification	kg SO2 eq
Eutrophication	kg N eq
Carcinogenics	CTUh
Non carcinogenics	CTUh
Respiratory effects	kg PM2.5 eq
Ecotoxicity	CTUe
Fossil fuel depletion	MJ surplus
Primary energy consumption (renewable + non-renewable)	TJ

2.1.4 Data Collection

The data quality and accuracy greatly impact the results, especially when aggregated over a 40 year time period. Huang et al. (2009) presented essential parameters/data required in developing an asphalt pavement LCA tool for only the construction/maintenance phase. Multiple data sources are used in the development of LCA-AIR. The material production (MP) and construction, maintenance and rehabilitation (CMR) phases use predominantly secondary data from the Ecoinvent database for materials and combustion of fuels. Some material's impacts come from the US National Renewable Energy Laboratory (US-NREL) and SimaPro databases. Construction equipment efficiencies and productivity use direct manufacturer equipment data when possible and complimentary data from the EPAs NONROADS (U.S. Environmental Protection Agency, 2008a). The use of secondary data is appropriate for the scope of this tool as it is for the US and not a specific geographic region.

2.1.5 Assumptions and Constraints of LCA-AIR in Study

The assumptions and limitations of the tool are the following:

- Dependency on secondary data sources.
- End of life phase for the pavement is excluded because prediction of pavement rehabilitation or airport reconfiguration decisions after 40 years has large uncertainty.
- New airfield construction requires soil removal to the depth of pavement structure.

- 90% of the maximum take off weight was used for each airplane type.
- Terminal and other aerial port infrastructure environmental burdens are excluded. These burdens include construction, energy use and waste generation from the terminal facilities, hangers, etc.
- The aircraft fuel consumption during flight at altitude is assumed to be constant with air resistance remaining constant.
- The airfield light emitting diode (LED) lights are assumed to run 12 hours per day.
- In the use phase, snow removal activities consume fuel during plowing operations but de-icing chemicals and distribution are not included in the LCA.
- Jet fuel consumption is modeled as kerosene combustion in industrial equipment.
- Construction and maintenance equipment only consider the diesel fuel consumed but equipment maintenance is not considered.
- For larger scale airfield projects, a concrete or asphalt plant is located on the airfield. This study assumes a 25-mile haul distance for ready-mixed concrete (PCC) and asphalt (AC).
- Feedstock energy is not considered.
- Construction activities are based on standard practices. Equipment productivities are based on average conditions and normal operator abilities.

2.2 Implementation Of The LCA-AIR

The implemented LCA in this study follows the framework described above. Figure 4 below, shows the information flow for each phase. First, the geometric data and associated information (density, jointing, etc.) is entered for use in the MP, CMR and use (U) phases. The processes for each phase are described below. Next, mix design material quantities are inputted to calculate impacts associated with the raw material extraction, processing, transportation to plant, mixing operations and transportation to the job site. Following the material inputs, the specific equipment for each construction tasks are selected. For example, land clearing may use dozers, front-end loaders and dump trucks. Based on the quantity of material to be removed, the associated productivity and fuel consumption rate are used to calculate the gallons of diesel consumed for each activity. From the quantity of diesel consumed the environmental impacts are then calculated. Lastly, information regarding airplane type, number of operations, snow removal, and lighting can be entered. Using the aforementioned data the environmental impacts for each phase as well as the total impacts are calculated for each of the TRACI indicator categories in Table 1.

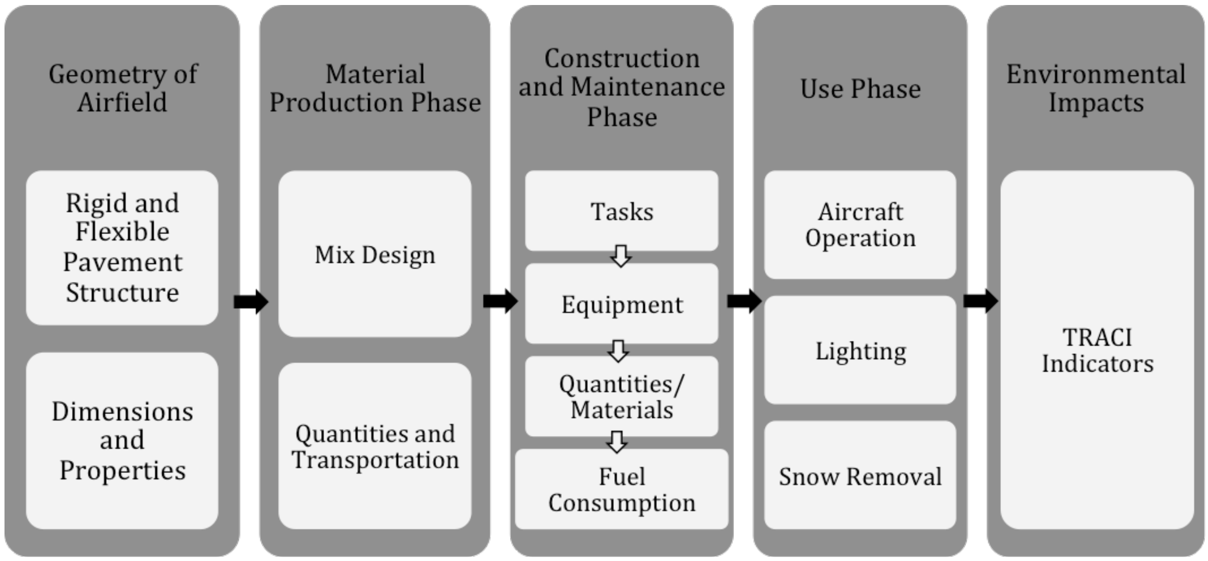


Figure 4 – LCA-AIR Tool Overview

An airport in a northern climate was analyzed in order to include an option for snow removal in the tool. Table 2 shows the airfield feature dimensions (Figure 2). Annual departures for the aircraft follow: B747 with 900, B777 with 500, A330 with 1200, and the B737 with 1200.

Table 2 - Case Study Feature Dimensions

Feature	Length (ft)	Width (ft)	Total True Area (sq ft)
Runway	11,800	200	2,360,000
Taxiway A	14,200	75	974,592
Taxiway A - Holding Pad	600	375	342,168
Taxiway B	900	75	83,892
Taxiway C	900	75	81,225
Shoulders (AC)	28,400	50	1,420,000

The environmental impacts for two different pavement structures (PCC and AC) were evaluated. The Federal Aviation Administration's (FAA) design program FAARFIELD is used to determine the pavement structure for a 40-year design life (Federal Aviation Administration, 2010). This extended design life has a higher initial cost than a standard FAA design life because of the increase in layer thicknesses. The PCC pavement life was assumed to be 40 years without major rehabilitation (includes some partial/full depth patch repair, joint/crack sealing, etc.) and the AC pavement structure has periodic rehabilitation (two mill/inlay operations, patching and crack sealing) over the 40-year life. Given the aircraft above, the flexible pavement consists of a five inch P-401 AC surface course, an 11 inch P-403 AC binder course over nine inches of P-209 crushed aggregate base and a subgrade California Bearing Ratio (CBR) of 10. The rigid pavement consists of 16.5 inch P-501 PCC (flexural strength of 700 psi) with 20 foot panel sizes, over six inches of P-306 Econocrete, over six inches of P-209 crushed aggregate base and a subgrade k-value of 141 lb/in^3.

2.3 Environmental Impact Results And Discussion

LCA-AIR was used to quantify the environmental impacts of the airport. LCAs commonly focus on energy consumed and global warming potential (GWP) for products or processes. All impacts are presented but energy and GWP are primarily considered for comparisons. This section presents the contribution to the impacts for selected phases (MP, CMR and U phase), and total impacts per functional units.

2.3.1 Material Production Phase Impacts

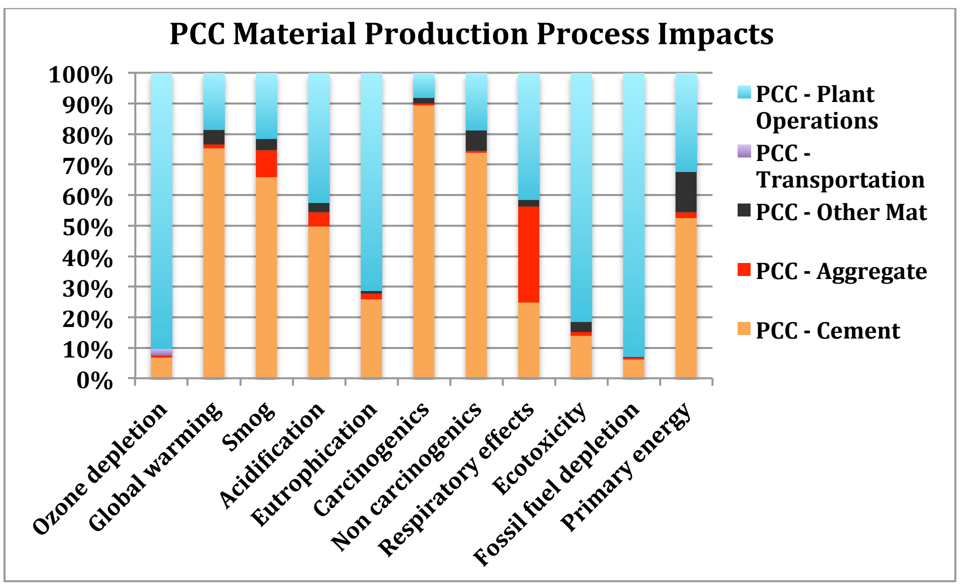
MP phase is broken down into the following five categories for PCC and AC: plant operations (all stages of mixing of PCC or AC), material transport to site, aggregate production (including recycled asphalt pavement and shingles), other material production (supplementary cementitious materials, steel, etc.), and cement or asphalt binder. The material impacts are independent of the mix design procedure (Superpave, Marshall, etc.) and are calculated as follows:

$$Total\ Impact_{material} = (V_{material})\ x\ (\gamma_{material})\ x\ (\varphi_{material})$$

where, $V_{material}$ is the volume (ft^3) of raw materials, $\gamma_{material}$ is the average material density (ton/ft^3) and $\varphi_{material}$ is the Ecoinvent environmental impact value per ton. The impacts for each material are summed together for a total impact per airport feature and phase. Although, roadways and airport pavement contain similar materials, the quantity per square yard differs. For PCC pavements, Figure 5 shows the binding material (cement) had the largest impact for GWP and energy followed by plant operations. For AC pavements plant operations had the largest impact for GWP and binder had the largest impact for energy followed by plant operations.

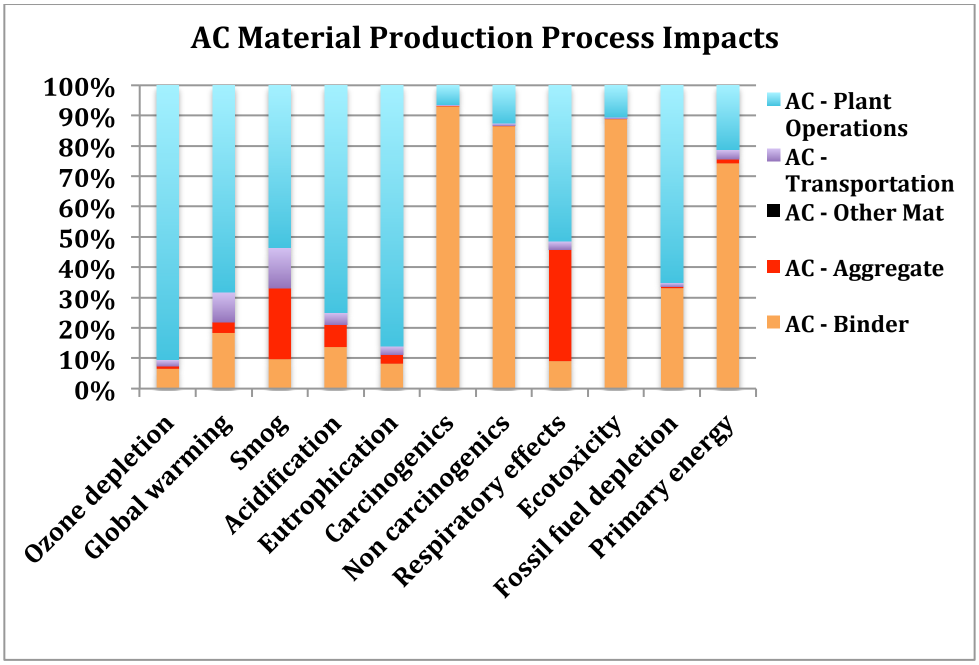
For PCC in Figure 5a, the cement accounts for 50% of the energy consumed and 72% of the GWP produced. The calcination of limestone in the cement production process requires large amounts of energy and releases significant quantities of CO_2. For AC in Figure 5b, the binder accounts for 74% of the energy consumed and 18% of the GWP produced. The extraction and processing of binder is extremely energy intensive at the refineries. Large amounts of energy are required during the asphalt production process as aggregates must be dried and heated prior to mixing with the binder. The quantities for the remaining categories are shown in Figure 5.

This data highlights areas where a reduction in environmental impacts can be achieved. The use of recycled, co-products, and waste materials (RCWMs) in the mix should be a balanced focus, considering both durability and performance for a specific pavement. Giustozzi et al. provided a large-scale (60,000 m^2) implementation of this concept, using 85% recycled and in-situ soil, material in an Italian taxiway. In doing so, a reduction of 35% CO_2 emissions was achieved for the entire project (Guistozzi et al., 2012).



(a) PCC

Figure 5 - Material Production Process Impacts



(b) AC
Figure 5 (cont.)

2.3.2 Construction/Maintenance and Rehabilitation Phase Impacts

The CMR phase is broken down into 30 categories as shown below. Based on required CMR schedule, not all categories were used for this hypothetical case study.

- Land Clearing and Removal
- Excavation (Edge Drains)
- Grading
- Earthwork
- Soil Stabilization
- Crushed Aggregate Base
- Asphalt Paving
- Concrete Paving
- Joint Sawing
- Pavement Marking
- Milling
- Cold In-Place Recycling
- Hot In-Place Recycling
- Full Depth Reclamation
- Rubber Removal
- Asphalt Patching
- Asphalt Overlay/Inlay
- Tack Coat
- Concrete Overlay
- Pavement Removal
- Diamond Grind Surface
- Surface Treatment
- Grooving
- Restriping
- Rubblization
- Concrete Demolition
- Rout and Seal Cracks
- Full Depth Repair (PCC)
- Partial Depth Repair (PCC)
- Joint Sealing

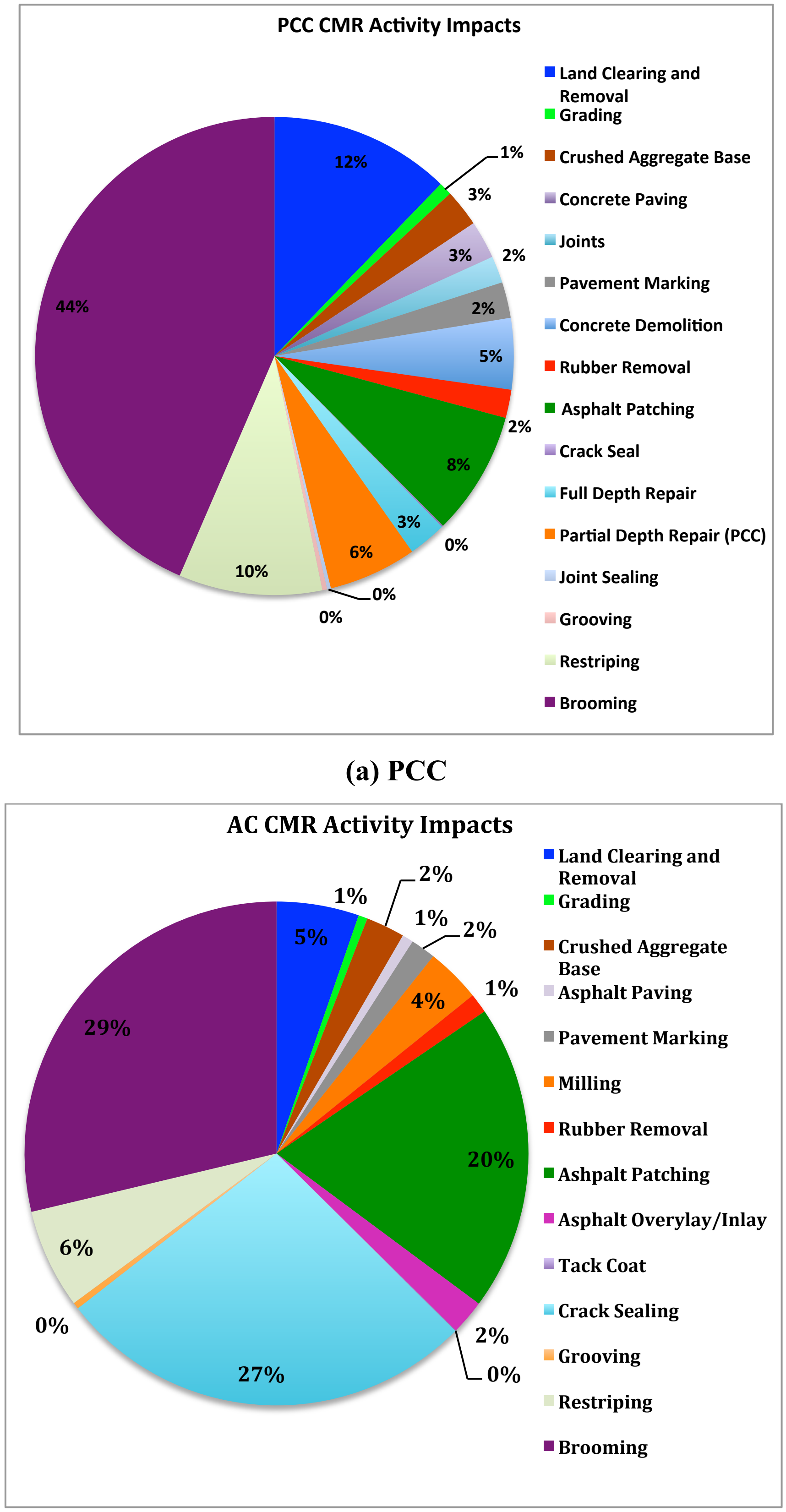
The impacts for the CMR activities stem from the combustion of diesel in the equipment. The repair materials are also included in this phase. Figure 6 shows the maintenance activities and associated percent fuel consumption for both pavements. The following equation was used to determine the fuel consumed and the impact from its combustion for each piece of equipment.

$$Total\ Impact_{construction} = \frac{V_{material}\ x\ \gamma_{material}\ x\ \Gamma_{equipment}\ x\ \varphi_{diesel}}{P_{equipment}}$$

where, $V_{material}$ is the volume (ft^3) of raw materials, $\gamma_{material}$ is the average material density (ton/ft^3), $P_{equipment}$ is the equipment productivity (tons/hr or ft^2/hour), $\Gamma_{equipment}$ is the fuel efficiency (gallons/hour) and φ_{diesel} is the Ecoinvent environmental impact value per gallon of diesel combusted.

Though material type and construction processes are similar to roadways, the material quantities and size of equipment per square yard differ for airports. Additionally, maintenance type and frequency differ on an airfield. Figure 6 shows the construction and maintenance activity contributions to environmental impacts. For PCC, the largest contribution for fuel consumption was brooming (43%) followed by land clearing (12%), and restriping (10%). Constant brooming of the airfield is one of the significant differences compared to roadway maintenance. Unlike vehicles, small, foreign object debris (FOD) poses a significant risk to aircraft and passenger safety. Therefore, maintenance crews must be vigilant in ensuring FOD is removed from pavement surfaces. Further evaluation of equipment used in land clearing for AC pavement, showed bulldozing and dump truck hauling accounted for 21% and 16% of initial construction impacts. This is similar to AC findings (24% and 18%, respectively) by Yang (2014). Specific impact analysis of paving equipment showed placement of crushed aggregate base course contributes as much or more than the actual paving itself (Guistozzi et al., 2012; Ferrebee, 2014).

AC construction and maintenance activities differed from PCC. Brooming was the largest contributor (29%) followed by crack sealing (27%) and asphalt patching (20%). Brooming and FOD removal do not change significantly with pavement type. The fuel consumption for AC maintenance is higher than PCC as expected because of more inlays and patching. Crack sealing, a time intensive activity, is required to minimize water infiltration into the flexible pavement structure and limit spalling. An additional difference with AC is the increase in restriping because of milling and inlay operations occurring two times (13 and 26 years) over the 40-year life.



(b) AC

Figure 6 - CMR Activity Impacts Based on Fuel Consumption

2.3.3 Use Phase Impacts

The use phase is broken into the following three categories: aircraft fuel consumption, snow removal operation (fuel consumption), and lighting (electricity usage). Lighting and snow removal showed small contribution to overall impacts. Lighting only showed a signification contribution (46.3%) in ozone depletion stemming from power plant generation. Snow removal impacts were the fuel consumption from operating a plow, rollover plow and a broom for 20 snowfalls per year. Aircraft fuel consumption dominates the use phase and subsequently the LCA impacts.

Figure 7 shows the cruising stage is the largest consumer of fuel followed by taking off stage. This study used 1,100 miles as the flight distance (approximately 2 hours). Taxi-out time is 20 minutes, taxi-in time is seven minutes and landing descent is five minutes. These times are similar to the times used by Wasuik et al. (2015) in accordance with the International Civil Aviation Organization (ICAO) guidelines. Take off (leaving pavement to cruising altitude of 25,000 ft.) accounts for 20 - 25% of fuel consumption per flight (Worldwatch Institute, 2005; Lewis, 2013) with LCA-AIR attributing 25% to take off. Cruising fuel consumption is based on the manufacturer's fuel efficiency of each aircraft. For this analysis and flight plan, the impact contribution from taking off is 25%, while cruising is 49%. As the length of flight increases, the cruising fuel consumption percentage will increase. For example, when the flight distance is increased to 5,500 miles (approximately 10 hours), LCA-AIR shows a contribution of 68% for cruising. The intensity of fuel consuming activities is critical for shorter flights.

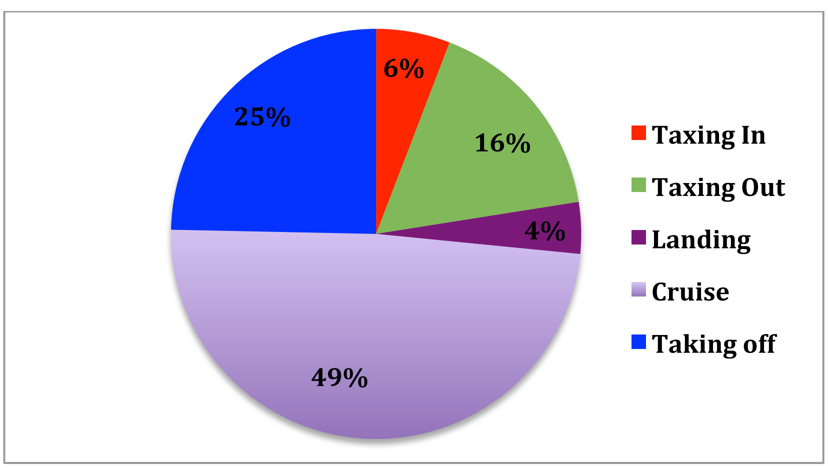


Figure 7 - Aircraft Operation by Stage

Roadway LCAs attribute fuel consumption to the pavement facility for each vehicle because of constant pavement-vehicle interaction. However, this pavement-vehicle interaction is negligible for airport pavement facilities with the aircraft traversing the pavement surface approximately 20 minutes before taking off. The IRI was calculated based on a regression curve adapted from highways (Wu, 2015):

$$IRI_t = (IRI_{t-1})\ x\ (a)\ x\ (h^b)\ x\ (Total\ operations^c)$$

where, regression coefficients *a, b and c* are: *a* is 21.9054 [PCC], 36,4843 [AC], *b* is -1.0612 [PCC], -1.3612 [AC], *c* is 0.13183 for both PCC and AC), *h* is the pavement thickness and *Total Operations* is the number of aircraft passes. LCA-AIR showed a 0.6% increase in fuel consumption because of a change in International Roughness Index (IRI) over time. The change in pavement roughness over time and rolling resistance has a minimal increasing effect on fuel consumption. Greater resistance and increased fuel consumption for airplanes is experienced from aerodynamic drag (Goldhammer & Plendl, 2014).

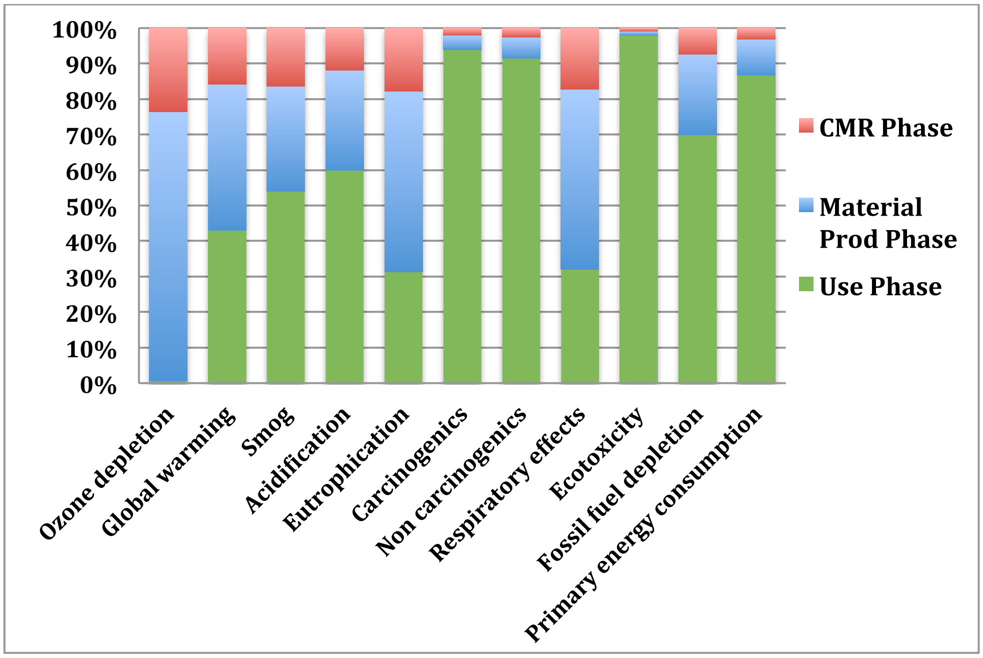
2.3.4 Phases Contribution to Total Impact

Figure 8 shows the impact percentages for the MP, CMR and U phase. For each pavement structure the U phase dominates, followed by MP, and finally CMR phase. Considering primary energy consumption, the U phase for PCC accounts for 85% and for AC it is 79%. Yang (2014) found the U phase accounted for 91%. This dominance over the other two phases is attributed to the aircraft operation over a 40-year period. MP for PCC accounts for 10% and AC accounts for 16%. The CMR for PCC accounts for 4% and for AC it is 6%.

Considering GWP, the U phase for PCC accounts for 42% and for AC it is 62%. The percentages for airfield pavements are approximately 40% lower than a roadway LCA (Yang, 2014). Materials production for PCC accounts for 42% and for AC, it accounts for 27% of the GWP. The higher percentage for PCC compared to AC is attributed to the carbonation of limestone in the cement production. The CMR for PCC accounts for 19% while AC it is 11%.

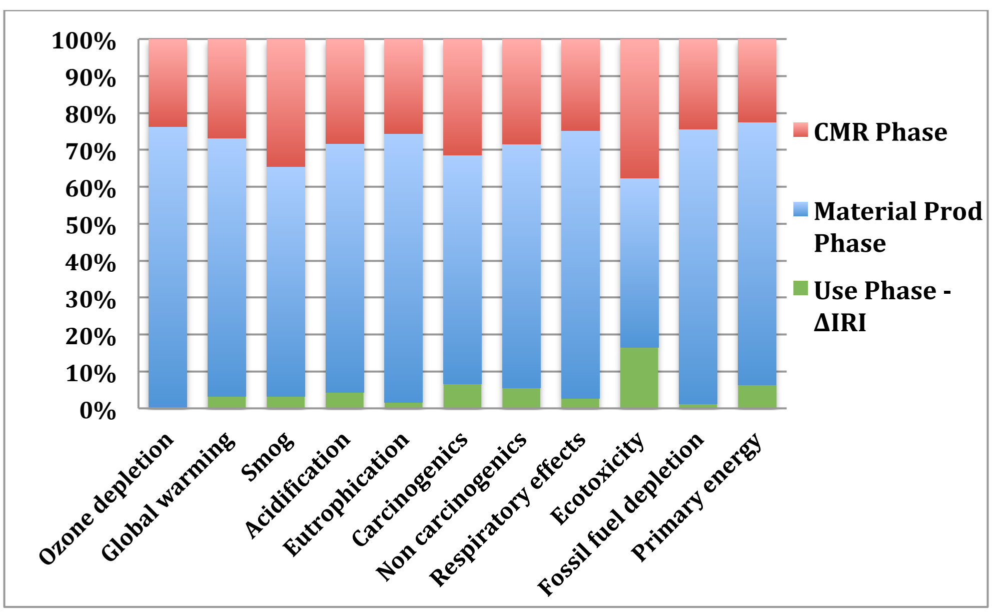
When only considering the additional fuel consumed because of a change in IRI in the use phase, the MP (~70%) and CMR (~28%) phases dominate as seen in Figure 8b and 8d. The change in pavement

IRI associated use phase has a limited impact, which is significantly different than for roadways (Wang et al., 2012; Yu & Lu, 2012). From a pavement sustainability standpoint, future improvements should focus on the MP and CMR phase.

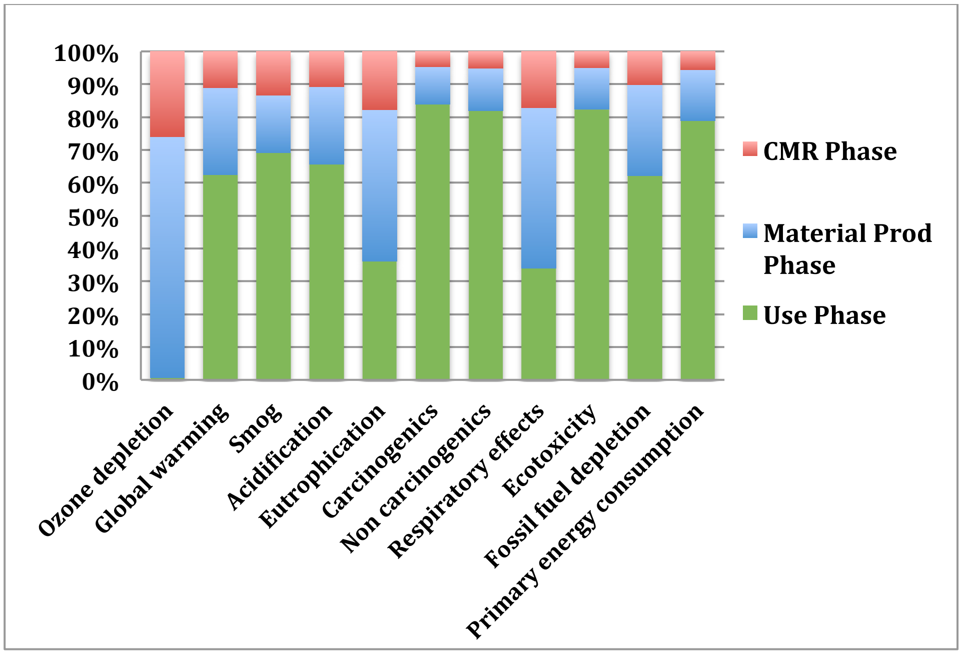


(a) PCC - considering total aircraft fuel in use phase

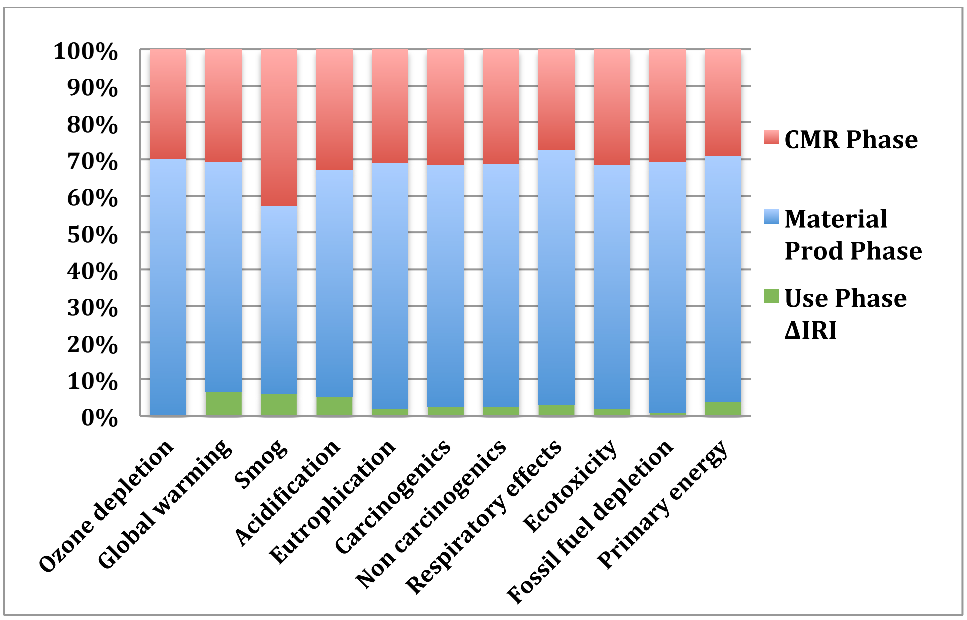
Figure 8 - Impacts by Phase



(b) PCC - considering only additional fuel consumed for ΔIRI in use phase



(c) AC - considering total aircraft fuel in use phase



(d) AC - considering only additional fuel consumed for ΔIRI in use phase
Figure 8 (cont.)

2.3.5 Impacts Per Functional Unit

Table 3 below, shows the impacts per functional unit for two sets of mixes for PCC and AC. One set used virgin material [no fly-ash (FA) and no recycled asphalt pavement (RAP), respectively]. The other set used fly ash and RAP, respectively. This table is for total impacts including half of the fuel consumed by the aircraft, which dominates the values. These specific impacts are for a hypothetical case study used to demonstrate the capability of LCA-AIR. These numbers are for specific pavement mix designs with associated maintenance and rehabilitation schedules mentioned previously. It is not meant to be a comparison of PCC and AC because of the differences in mix designs and their relative impacts. For example, the AC mix with recycled material used 28% RAP in the base course layer, where the concrete did not use recycled aggregates. However, PCC used 25% FA as supplementary cementitious material. For each impact category a reduction with the use of recycled material is seen. The replacement of cement with FA and subsequent reduction in limestone calcination reduced the GWP and fossil fuel impacts for PCC.

Table 3 - Total Impacts per Functional Units for Hypothetical Case Studies
a) Virgin mixes

Pavement Type		PCC		AC	
Impact category	**Unit**	**Total Impact Per yd²**	**Total Impact Per lbs-mile**	**Total Impact Per yd²**	**Total Impact Per lbs-mile**
Ozone depletion	kg CFC-11 eq	7.096E-05	5.255E-18	6.522E-05	5.260E-18
Global warming	kg CO2 eq	3.560E+02	4.540E-09	1.770E+02	4.545E-09
Smog	kg O3 eq	3.107E+01	5.882E-10	1.905E+01	5.888E-10
Acidification	kg SO2 eq	2.319E+00	5.213E-11	1.849E+00	5.218E-11
Eutrophication	kg N eq	2.969E-01	2.847E-12	2.346E-01	2.850E-12
Carcinogenics	CTUh	7.253E-06	3.984E-16	8.747E-06	3.988E-16
Non carcinogenics	CTUh	7.407E-05	3.826E-15	8.803E-05	3.830E-15
Respiratory effects	kg PM2.5 eq	1.262E-01	1.224E-12	1.149E-01	1.225E-12
Ecotoxicity	CTUe	1.177E+03	7.400E-08	1.681E+03	7.408E-08
Fossil fuel depletion	MJ surplus	1.627E+03	5.239E-08	1.943E+03	5.244E-08
Primary energy consumption (renewable + non-renewable)	TJ	8.239E-03	3.766E-07	9.369E-03	3.770E-07

Table 3 (cont.) b) Recycled material

Pavement Type		PCC		AC	
Impact category	Unit	Total Impact Per yd^2	Total Impact Per lbs-mile	Total Impact Per yd^2	Total Impact Per lbs-mile
Ozone depletion	kg CFC-11 eq	6.782E-05	5.255E-18	6.512E-05	5.260E-18
Global warming	kg CO2 eq	2.970E+02	4.540E-09	1.761E+02	4.545E-09
Smog	kg O3 eq	2.761E+01	5.882E-10	1.886E+01	5.888E-10
Acidification	kg SO2 eq	2.107E+00	5.213E-11	1.841E+00	5.218E-11
Eutrophication	kg N eq	2.742E-01	2.847E-12	2.339E-01	2.850E-12
Carcinogenics	CTUh	6.963E-06	3.984E-16	8.744E-06	3.988E-16
Non carcinogenics	CTUh	7.077E-05	3.826E-15	8.799E-05	3.830E-15
Respiratory effects	kg PM2.5 eq	1.182E-01	1.224E-12	1.115E-01	1.225E-12
Ecotoxicity	CTUe	1.175E+03	7.400E-08	1.680E+03	7.408E-08
Fossil fuel depletion	MJ surplus	1.592E+03	5.239E-08	1.941E+03	5.244E-08
Primary energy consumption (renewable + non-renewable)	TJ	7.860E-03	3.766E-07	9.354E-03	3.770E-07

2.4 Conclusion

LCA-AIR was developed to provide a sustainability LCA tool for airport owners, operators and engineers to quickly determine the environmental impacts related primarily to airfield pavement and maintenance activities. LCA-AIR requires inputs on the following: airfield geometry, materials and equipment required for construction, maintenance and rehabilitation, as well as airfield use and aircraft operation. It does not consider the end of life phase for pavement or life cycle impact of aircraft manufacturing, maintenance, and disposal. Terminal activities and associated impacts are also excluded. LCA-AIR calculates the environmental impacts for each phase and total impacts per functional unit (square yard and pound-mile traveled) using TRACI indicator categories.

Like roadway pavement LCAs, LCA-AIR showed the use phase dominates the impacts followed by material production and CMR when total fuel consumption is considered. This is attributed to the aircraft operation over the design life. Binding agent had the greatest contribution to the materials production phase for PCC followed by plant operations and the opposite was found for AC. Brooming the pavement surface, to remove FOD, regardless of pavement type, showed the largest contribution over the design life in CMR. For the use phase the aircraft fuel consumption plays a significant role in energy and emissions. Cruising has the largest contribution and take off has the greatest fuel consumption intensity. Unlike highway LCAs, IRI contributes minimally to fuel consumption because of the short period of pavement aircraft tire interaction.

CHAPTER 3 – O'HARE INTERNATIONAL AIRPORT TAXIWAY A & B INTRODUCTION

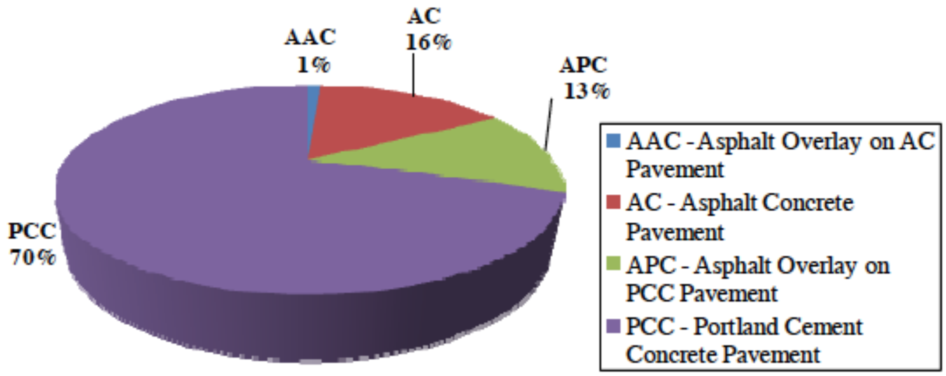
The pavement structure of Chicago's O'Hare International Airport (ORD) Taxiways A & B, surrounding the main terminal, is reaching the end of its performance life and is in need of rehabilitation. There are various distress types and severity levels in the pavement structure. In addition to loading and environmental factors, inadequate site, surface, and subsurface drainage may be contributing to the pavement structural condition and impact future rehabilitation choices. Additionally, ORD airport engineers have noted the geometrics of the taxiways are not in compliance with current FAA standards.

Multiple rehabilitation strategies are likely needed to correct the existing pavement condition while meeting the constraints of the owners and operators. In order to provide a suitable list of potential rehabilitation strategies, an assessment of TW A & B's pavement layer inventory, structural condition, layer material properties, and surface and subsurface drainage condition must be completed. This information coupled with existing field data, as-built design information, and engineer site experience can be integrated into the final strategic rehabilitation options for these taxiways. These rehabilitation options may include but are not limited to individual slab replacement or maintenance, mill and overlays, rubblization with overlay, full reconstruction, precast concrete panels, and drainage replacement or maintenance.

3.1 Background of Taxiway A & B

ORD was selected in 1945 to be a commercial airfield and opened for commercial traffic in 1955 with four runways serving 176,902 passengers. The airport grew and claimed the 'worlds busiest airport' for the first time in 1962 (Chicago Department of Aviation, 2015). This growth continued as a premier airport and was ranked again the busiest (arrivals and departures) airport in the world per the FAA Air Traffic Activity System (ATADS) (Federal Aviation Administration, 2015). Currently, ORD operates eight runways with 5.38 million square yards of airside pavement distributed between nine runways (RW) (1.11 million square yards), taxiways (TW) (2.11 million square yards) and aprons/hold pads (1.9 million square yards). Figure 9, from the 2011 Condition Report, shows 70% of the surface type breakdown at ORD is PCC. Sustaining and increasing achieved growth requires around-the-clock maintenance, repair and rehabilitation of these pavements.

Figure 9 - ORD Pavement Surface Type



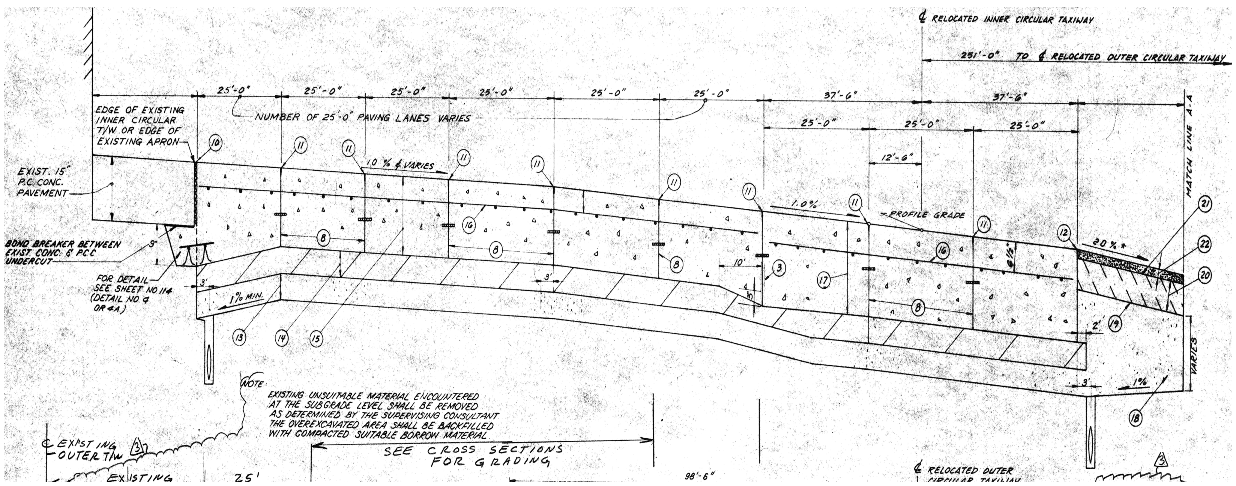
3.2 Taxiway A & B Pavement Structure

The pavement is reaching the end of its performance life and is in need of rehabilitation. Based on as-built data provided by ORD engineers, the TWs were constructed between 1986 and 1988 over cohesive soils with varying amounts of sand. The approximate length of each taxiway is 11,088 feet. Table 4 summarizes the typical pavement section. Figure 10 and Figure 11 show the section from as-built drawings. Coring data from 2007 and 2013 showed PCC surface ranges from 19-1/2 inches to 25.5 inches with an average of 21.96 inches. The asphalt base ranges from 0 inches to 9 inches thick with an average of 5.31 inches. The aggregate base layer ranges from 0 inches – 20 inches with an average of 5.51 inches thick (MACTEC, 2007; Chicago Airports Resources Enterprise, 2014). These values are tabulated in the Table 24 and Table 25, in the Appendix.

Table 4 - Pavement Section Summary

TW (Typ)	Thickness (in)		Shoulders	Thickness (in)
PCC	21		**AC Surface Course**	2
AC Stabilized Base (BAM)	6		**AC Base Course**	7
Frost Protection Course	6		**Frost Protection Course**	Varies (min 6”)

- 25ft x 25ft panels everywhere
- At 6.5" from surface, wire fabric 6"x6" (W6xW6 wire 0.058in^2/ft)
- 8" dia. longitudinal edge drains perforated ESVCP at 3ft offset
- 1.5" dia dowel bars, L=30” @12" o.c. @ depth of 6.5"
- Hinged butt joint – L=30inch #11 bar @12” o.c.



LEGEND

3 THICKENED EDGE EXPANSION JOINT FOR RUNWAYS, TAXIWAYS & APRONS

4 TRANSITION - NEW TO EXISTING PAVEMENT

8 HINGED BUTT JOINT

10 EXPANSION JOINT SEAL

11 HINGED JOINT SEAL

12 TAXIWAY - SHOULDER SEAL

13 6" FROST PROTECTION COURSE

14 6" STABILIZED AGGREGATE BASE COURSE (B.A.M.)

15 18" P.C. CONCRETE PAVEMENT

16 PAVEMENT REINFORCEMENT - 6 X 6 - W6 X W6 WIRE FABRIC

17 21" P.C. CONCRETE PAVEMENT

18 VARIABLE THICKNESS FROST PROTECTION COURSE

19 BITUMINOUS PRIME COAT

20 7" BITUMINOUS BASE COURSE

21 BITUMINOUS TACK COAT AS DIRECTED BY COMMISSIONER

22 2" BITUMINOUS SURFACE COURSE (TAXIWAY)

23 4" TOPSOIL/SEEDED

Figure 10 - Taxiway A Section (Typical)

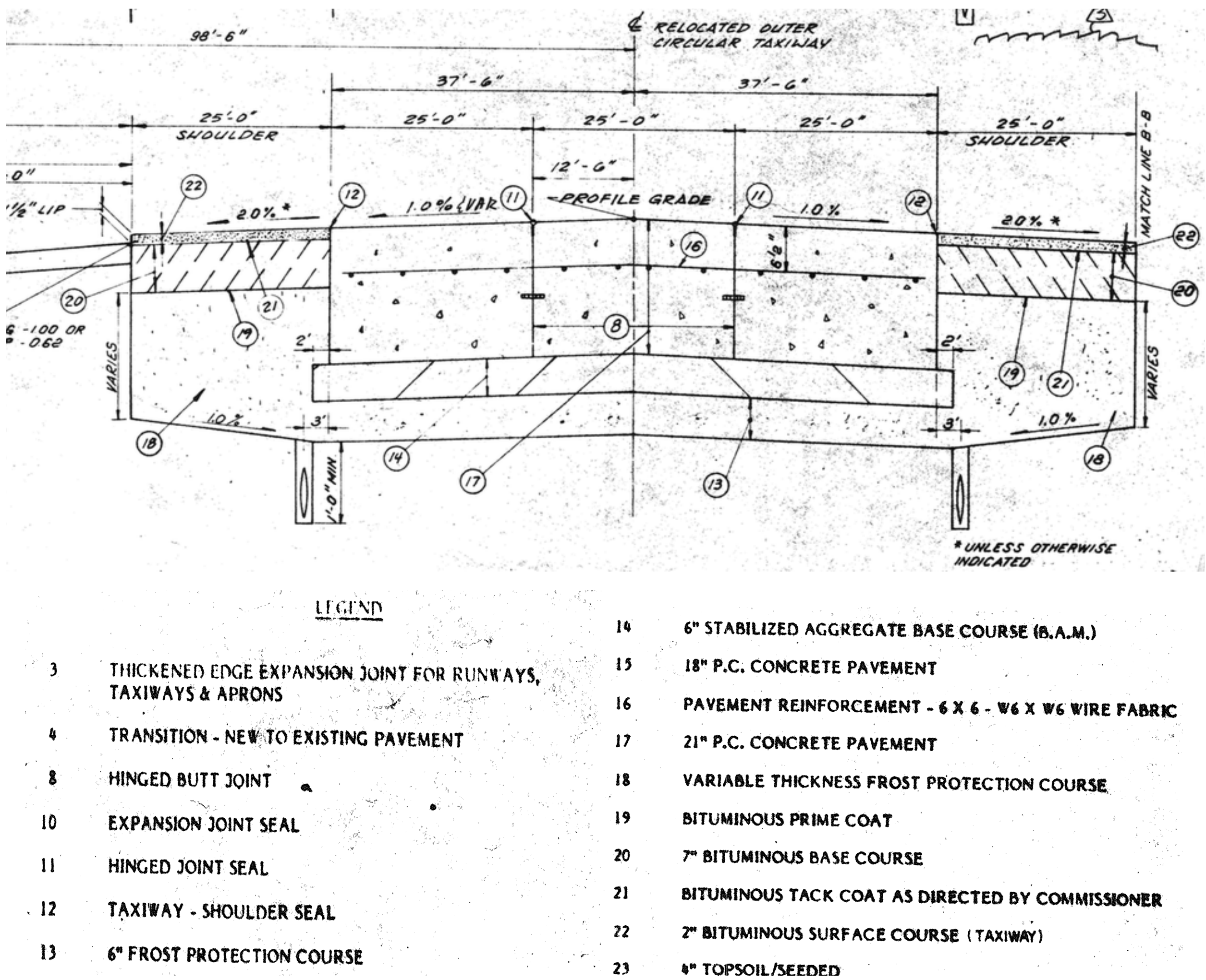


Figure 11 - Taxiway B Section (Typical)

3.3 Past Condition Assessments

PCIs are completed every three years at ORD. PCI surveys and associated 10-yr maintenance plans were provided dating back to 2005 (MACTEC, 2005; MACTEC, 2008; Edwards and Kelcey Desing Services, Inc., 2011). There are various distress types and severity levels in the pavement structure as seen in Figure 117 to Figure 120 in the Appendix. The PCI and 10-year investment maps can bee seen in the Appendix in Figure 121 to Figure 126. Since 2005 a majority of sections had a PCI of 0 – 70, indicating a need for major rehabilitation or reconstruction. By 2011 a majority of sections required reconstruction. There is inherent variability between surveys because of human factors and the perceived severity of distresses. To reduce error, LIDAR and laser scanning images can be used to determine a new panel-by-panel PCI. The PCI survey is also a surface distress survey and not a structural capacity assessment. In areas where inlays have occurred, the PCI will be a higher value because of the new surface, but may not be indicative of the whole pavement structure condition.

3.3 Taxiway Traffic Density

Traffic operation projections for 2018 were provided by Ricondo and Associates, Inc from the 2013 review of the 2005 Environmental Impact Study (Federal Aviation Administration, 2005). Traffic operations were broken down into aircraft Categories 1 – 8 based on maximum takeoff weight (MTOW) as seen below in Table 5 and Table 6. Operations were provided for each aircraft at specific links on each TW.

Table 5 - Aircraft Categories MTOW

Group	Aircraft MTOW (lbs)
Group 1	65,000 or less
Group 2	65,000 - 150,000
Group 3	150,000 - 200,000
Group 4	200,000 - 300,000
Group 5	300,000 - 450,000
Group 6	450,000 - 600,000
Group 7	600,000 - 800,000
Group 8	800,000 or more

Table 6 - Aircraft Used for 2018 Operation Projections and Associated MTOW

Group	Model	Aircraft MTOW (lbs)
1	CRJ-200	47,450 - 53,000
	E140/145	48,500 - 53,131
	Miscellaneous	Various
2	B717	121,000
	B737-200/300/400/500	128,100 - 150,000
	CRJ-700	84,500
	CRJ-900	84,500
	DC-9-30/50	110,000 - 121,000
3	A319/320/321	154,322 - 196,209
	B727F	191,000
	B737-700/800/900	154,500 - 187,700
	MD80	140,000 - 172,000
4	B757-200	255,500
	B757F	255,500
5	A300/310F	363,800 - 375,900
	B767-300	350,000
	B767F	350,000
	DC-8F	355,000
6	A330-200/300	513,675 - 524,700
	A340-200/300/600	606,271 - 811,301
	MD10/11F	580,000 - 618,000
	MD11F	618,000
7	B777-200	766,000
	B777-200/300	766,000 - 775,000
8	A380	1,234,588
	B747-400	875,000
	B747F	875,000

An analysis was completed to determine total operations at each link and determine which groups accounted for the majority of operations. Total predicted operations on TW A & B are 9.02 million in 2018. Groups 1-3 account for 90.2% of operations (8.317M). Groups 1-4 account for 90.3% of operations (8.324M). Groups 1-5 account for 93.7% of operations (8.5M). Groups 1-4 was determined to be the dividing line for combined analysis with other survey methods. Operations in Groups 1-4 ranged from 4,296 at link 1 to 432,670 at link 35. Figure 12 shows total yearly operations projected for 2018 in Groups 1-4. Certain links have a higher number of operations from heavier aircraft. These links are shown below in Table 7.

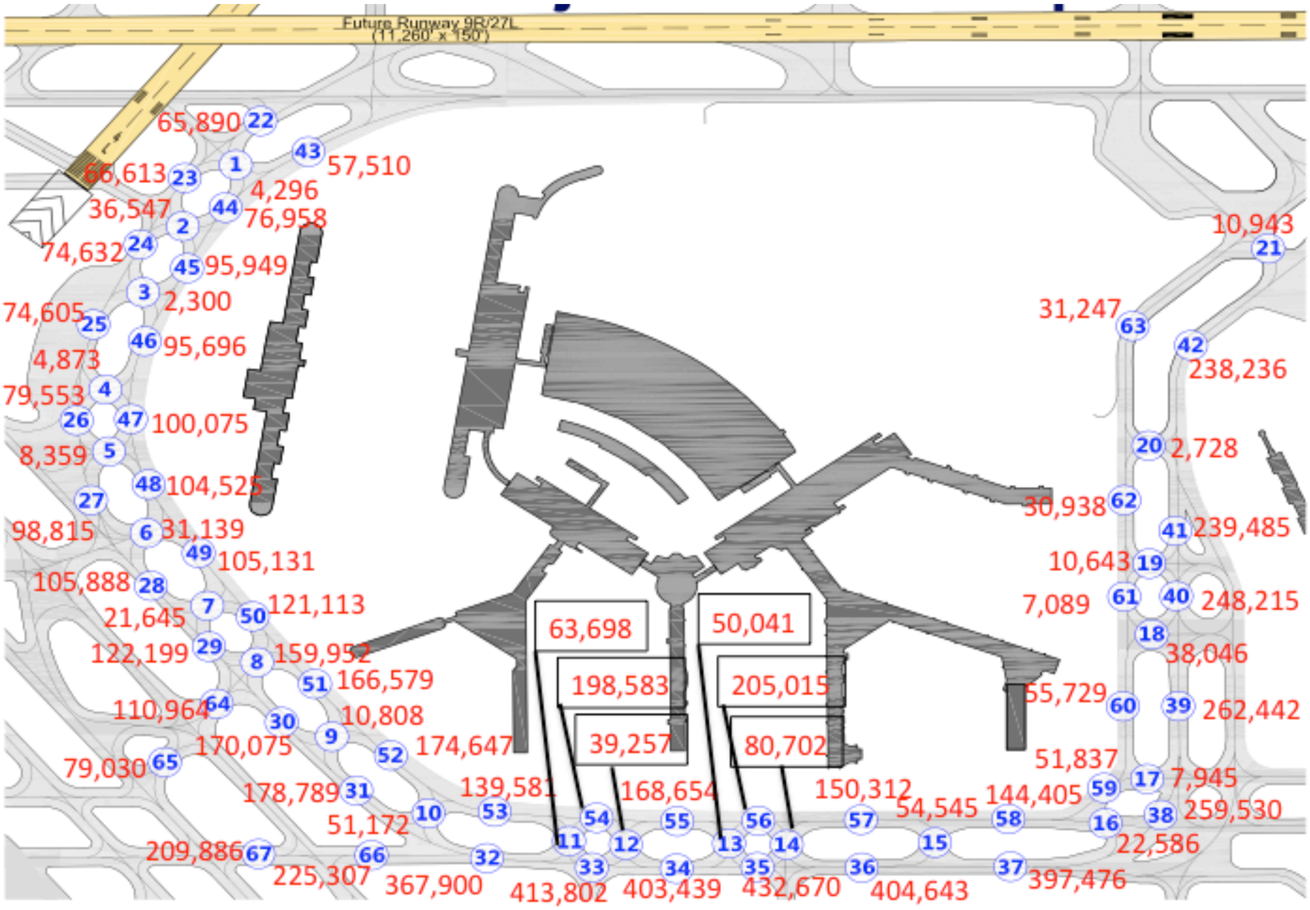


Figure 12 - 2018 Projected Annual Operations for TW A (inner) & B (outer) (Groups 1-4)

Table 7 - Links with Operations Greater than 20% in Aircraft Groups 5-8

Link	% of Ops > 20% in Grp 4-8	Link	% of Ops > 20% in Grp 5-8	Link	% of Ops > 20% in Grp 6-8
3	38%	**3**	38%	**3**	38%
16	25%	**16**	25%	**16**	21%
19	44%	**19**	44%	**20**	27%
20	63%	**20**	63%		
61	22%	**61**	22%		

A traffic density map was generated based on traffic operation groupings of 50,000. This provides a visual representation of traffic from white (low traffic) to red (high traffic). This map will be used in conjunction with HWD testing, pavement condition assessments (LIDAR/Lasers) and hydraulic topography to provide a comprehensive view and determine possible correlations for distresses. This map can be seen below in Figure 13.

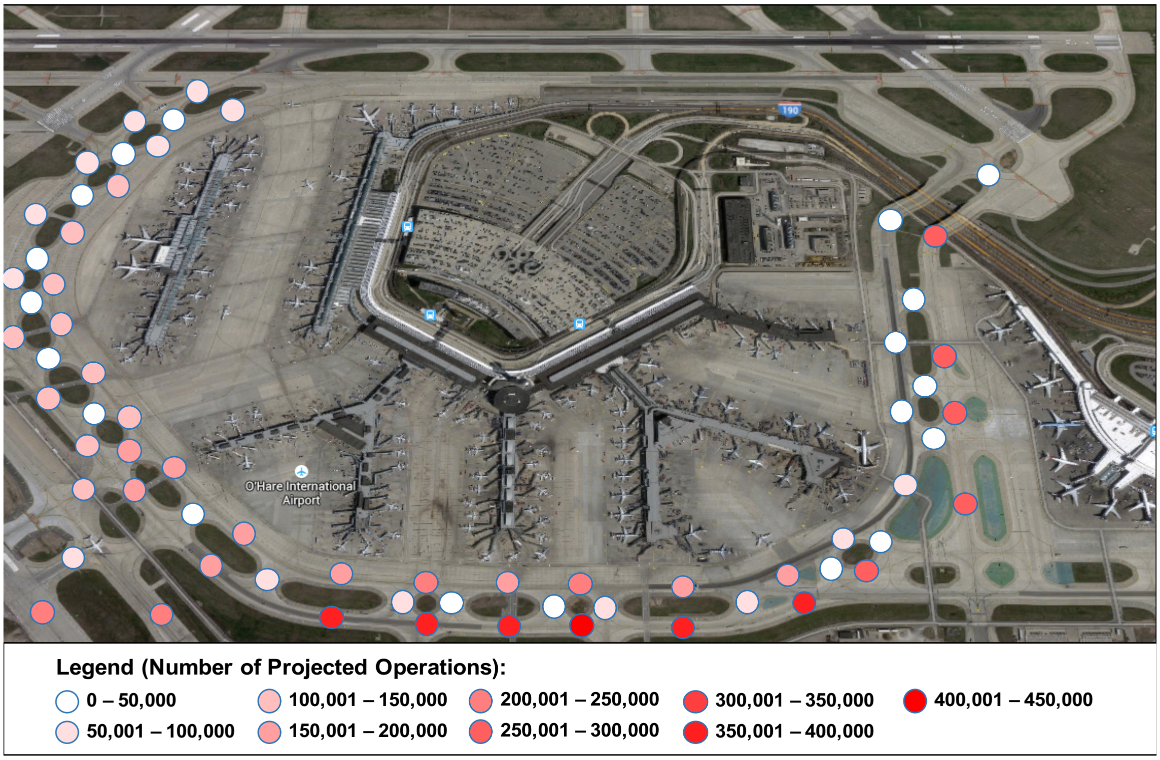


Figure 13 - Taxiway A &B Traffic Density Map

CHAPTER 4 – PRECAST CONCRETE PANELS

Rapid airfield repairs have origins with the Department of Defense (DoD) and their need to repair pavements during wartime operations in order to launch and recover aircraft against enemy forces. Cast in place (CIP) may require multiple days to cure thus inhibiting above objectives from being met. The ability to rapidly repair airfield pavements is also critical for commercial airfields. The shear volume of traffic has grown nearly ten fold in 50 years and any closure or delay cost airport owners, operators and passenger. Rapid repairs or fast track repair techniques minimize these closures and delays. Fast track repairs include all aspects of planning, design and construction to provide early opening of repaired facilities (Olidis, Swan, & Saeed, 2010). Perhaps the best know feature of fast track repairs is the use of high-early-strength concrete. Some airports, such as Seattle-Tacoma International and Lambert-St. Louis International, have employed rapid setting concrete for repairs with good performance (Wessels, 2015; Sander, 2015). Another advancing technology in the rapid repair and reconstruction arena is the use of precast concrete panels (PCP), which is the focus of this chapter.

4.1 Definition of Precast Concrete Panels

PCPs are modular pavement slabs fabricated on/off site, transported to the project site and installed on a prepared base (existing pavement or re-graded foundation) (Federal Highway Administration, 2010). PCP can be used for intermittent or continuous repairs. There are different slab types including; nominally reinforced (for transport and handling loads), pre-stressed precast concrete panels (PPCP) and post-tensioned precast panels. Combinations of pre-stressed and post-tensioned precast panels have also been used in highway pavements. The origins, advances and methods are discussed later. Common advantages and disadvantages are seen below.

Advantages	**Disadvantages**
- Shortened installation/closure time compared to CIP	- Higher cost than CIP and rapid set
- Higher quality concrete	- Less experienced contractors
- Controlled fabrication conditions	- Size for transport/workability
- Flexible weather installation	
- Increase in safety for workers	
- Mass-produce and store until needed	

The use of PCP in the United States was sporadic and was 'proof of concept' prior to 1995 for highways and airfields. Exiting literature is very limited. One of the earliest uses of PCP in US highways was in South Dakota in 1960. It was a research project by South Dakota State University and the South Dakota DOT. They used 6 ft x 24 ft x 4.5 in pre-stressed panels with a 'tongue and fork' connection followed by an asphaltic overlay as seen below in Figure 14. Issues with reflective cracking shortly appeared and has subsequently been overlaid with asphalt. The road system was still in service in 2000 (Merritt, McCullough, Burns, & Schindler, 2000).

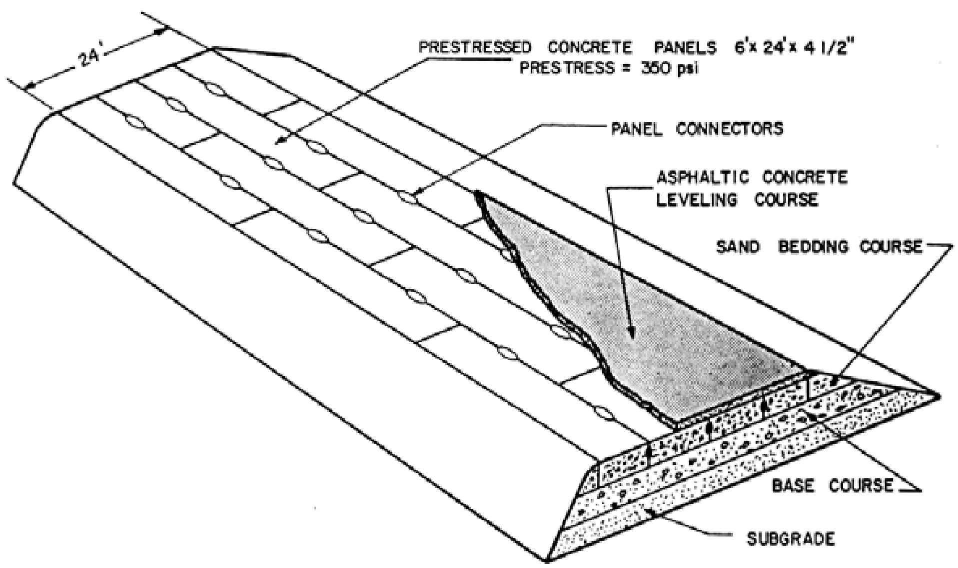


Figure 14 - South Dakota PCP construction in the 1960's
(Merritt, McCullough, Burns, & Schindler, 2000)

Table 8 - Early literature on precast repairs

Title	Author(s)	Year
Concrete Pavement Joint Repair With Pre-cast Slabs	Simonsen, J.E.	1971
Concrete Pavement Joint Repair With Pre-cast Slabs, Part 2	Simonsen, J.E.	1972
Thruway Repairs Concrete Slabs Overnight	Overacker, J.W.	1974
An Approach to Concrete Pavement Replacement That Minimizes Disruption of Traffic	Grimsley, R.F.; Morris, B.G.	1975
Full-depth Repair of Jointed PCC Pavements Cast-in-place and Precast Procedures	Tyson, S.S.	1976
Precast Repair of CRC Pavement	Meyer, A.H.; McCullough, B.F.	1983
The Use of Precast Concrete Raft Units for Roads.	Bull, J.W.	1988

The former Soviet Union placed it's first precast concrete airfield pavements in 1931-1932 using a hexagonal design (4 foot long sides and depth ranging from 4 – 5.5 inches). Due to increased loads, these sizes increased and in the 1950's traditional rectangle slabs became available. Figure 15 below, shows the hexagonal precast slabs that were still in use in 2007. Figure 16 shows the rectangular slab with the welding ties (Sapozhnikov & Rollings, 2007) . The Japanese (as early as 1970's) have used precast slab panels in various applications, including airports, highways, tunnel pavements, and high-speed slab track. During the commencement of conflict in Afghanistan, US military encountered precast paving by the former Soviet Union (placed in 1980's) on several airfields (Tayabji, Buch, & Kohler, 2008).

Figure 15 - Soviet Precast Hexagonal Concrete Slabs (approximately WWII Era)
(Sapozhnikov & Rollings, 2007)

Figure 16 - Soviet Precast Airfield Slabs
(Sapozhnikov & Rollings, 2007)

One of the earliest North American airfield installations was at the San Diego International Airport. In the early to mid 1970s a second runway needed to be constructed. However, the existing runway needed to remain open and 116 slabs were in great need of rehabilitation (Engineering News Record, 1981). Due to the questions regarding the durability of rapid setting concrete at the time, PCPs were the solution. The new slabs were two inches smaller than the existing and had the lifting devices cast into the slab. A different technique was used to remove the existing panels than typically seen today (lift-out or demolish and remove). The joints were saw cut and a six foot square was cut in the center of the slab to reduce possible edge damage to the existing slab by letting the slab 'fall inward' (Barenberg, 1996). After the slab and six inches of base material was removed, a lean concrete was placed (flowable) and screeded level. The PCP was set and compacted with a small steel-wheeled vibratory roller (10-ton) with most roller weight was on the existing slabs. The flowable material came out of the weep holes and some joints. After setting, the runway was open to traffic at 6:00 a.m. hours each day. Two slabs were completed each night. Initially, no load transfer devices were installed. However, after all slabs were replaced, six-inch cores were taken at joint locations and load transfer devices were installed. The exact type of load transfer device was not known. As a final step, the airfield was overlaid with eight inches of asphalt (Rollings & Cho, 1981).

The second, more recent installation was at Calgary International Airport in the early 1990s and was still in good condition in 2015 (Botero, 2015). Subsequently, pilot project airfield installations at large commercial airports were done including LaGuardia Airport, Washington Dulles International Airport and Lambert-St. Louis International Airport, which are discussed in more detail below.

The first major US government push for precast development occurred in the late 1990's when the FHWA Concrete Pavement Technology Program funded a PCC rehabilitation development project at the University of Texas at Austin. This system consisted of pre-stressed panels in the transverse direction and post-tensioned in the longitudinal direction along with other panels in the field. Seating the panels was accomplished by injecting a bedding grout under the slab. Based on their work at the Center for Transportation Research, Texas DOT completed the first pilot project using prestressed, precast concrete panels (PPCP) in March 2002. The FHWA also funded further research and field trials at Michigan State University. Subsequent pilot projects have been performed for DOTs across the United States. The private sector has also worked on the development of PCP with systems such as the Fort Miller Super Slab system, Uretek Stitch-in Time system, Kwik Slab, Barra Glide, ModieSlab, other generic versions, etc. With the development and use of each system, the number of lane miles constructed with Precast Pavement Systems (PPS) has increased steadily since 2000 as seen below in Figure 17. A Tech Brief by the FHWA contains a comprehensive list of PCP projects for highways (Tayabji & Brink, 2015). The use of (PPS) in airports is less common but their use shouldn't be barriers for immediate implementation.

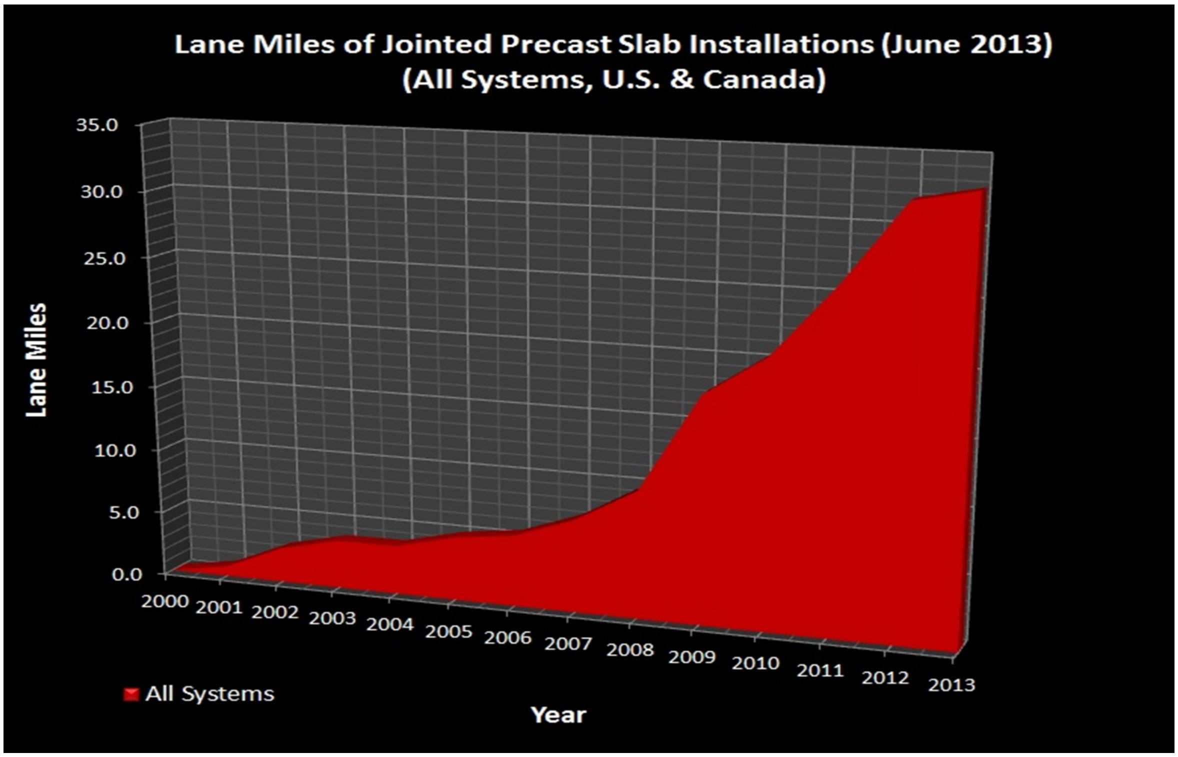


Figure 17 - Precast Pavement Use in the U.S. and Canada
(Buch & Snyder, 2015)

4.2 Precast Concrete Panel Systems

Multiple PPS have been developed to enhance the rapid pavement repair techniques and efficiencies. A short description and discussion is below for each. This provides engineers with the opportunity to select the method/combination of methods, which will best suit their needs. PPS have similar construction methods; primarily, slab casting, existing slab removal, base preparation, placing precast slab, setting/grouting of slab and other finishing activities such diamond grinding or marking. These methods are shown below in Figure 18. Individuals systems are discussed after in further detail.

(a) Casting and finishing slabs

Figure 18 - Precast Generalized Methods (a-d)

(b) Sawcut slab/dowels and remove existing slabs

(c) Base preparation and new slab placement

(d) Base grout injection and dowel grouting

Figure 18 (cont.)

4.2.1 Fort Miller Super-Slab System

The Fort Miller Super-Slab system is a proprietary and patented method first used in 2001. The Super-Slab method has been used in airports and highways. A local casting contractor and installer work with a company representative to accomplish the work under the patent. A complete list of projects (approximately 2.3 million square feet) through 2014 can be seen on their website.

There are notable differences with this method compared to other PCP methods. A majority of these differences occur during the slab casting. The precast process occurs in a controlled environment with high quality concrete. First, the dowel and tie bar slots are dovetail-shaped on the bottom of the slab as compared to a traditional dowel slot in Figure 19. This provides mechanical interlock between the grout and precast concrete verses vertical slots as seen in load transfer retrofits and other generic precast panels. Slots on the bottom also provide a high quality PCC surface, which is exposed to loading and the environment. Having the dowel slots on the bottom of the slap provides enhanced protection of the dowel bars from deicing salts and snowplows. The mortar grout used to top-fill traditional dowel slots is produced in the field and is design for a rapid set which can cause durability issues if not done properly.

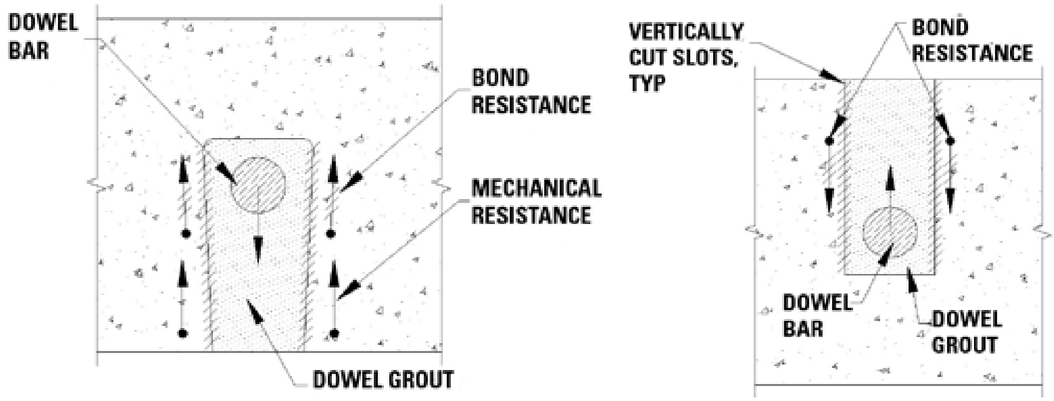


Figure 19 - Super-Slab Dowel Bottom Slot (left) and Generic Dowel Top Slot (right)
(Smith P. J., 2008)

The second difference is grout distribution channels on the bottom side of the slab as seen below in Figure 20. This helps uniform distribution of the grout to ensure full contact is achieved between the slab and the base material. The third difference is the foam gasket attached to the underside of the slab to prevent grout material from entering both the dowel slots and joints. Grout in either of these to locations will compromise the performance life of the pavement. The fourth difference is the ability to fabricate warped slabs (three-dimensional) to meet the needs of superelevation transitions, curves, ramps, etc. (Smith P. J., 2008). A rendering of the warped slabs is seen in Figure 21. Multiple projects across the US have successfully implemented this slab type.

Figure 20 - Super-Slab Precast Panel (grout channels, foam gasket and dove-tail dowel slots)
(Smith P. J., 2008)

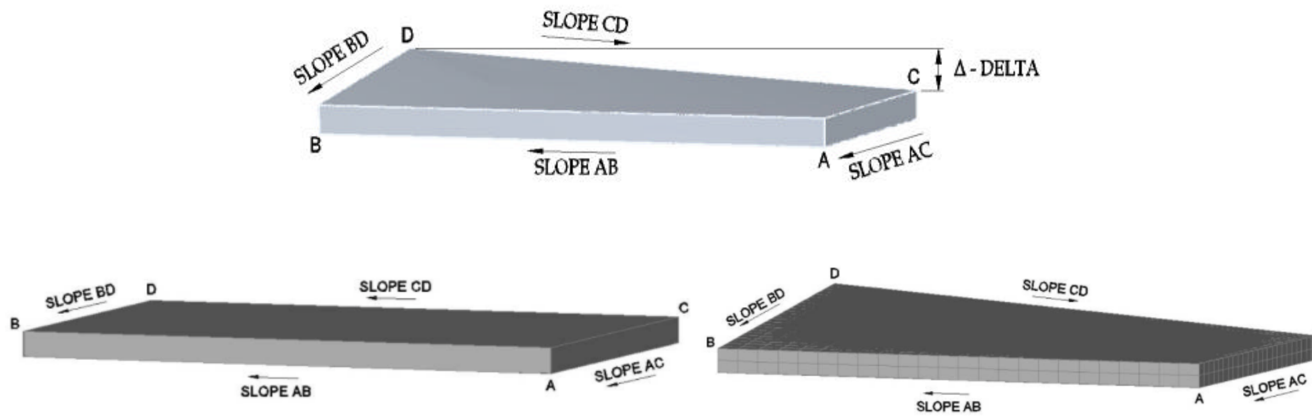


Figure 21 - Super-Slab System - Warped Slab Rendering

(Smith P. J., 2012)

Single Plane – opposite side slopes are equal   Warped Plane - opposite side slopes are unequal

4.2.2 URETEK Stitch-In Time System (discontinued)

The Stitch-In Time Method is a proprietary used on both highways and an airfield in the early 2000s. There are two proprietary components of the system are worth mentioning. First, the precast systems used fiberglass slats in lieu of dowel bars (Figure 22). The stitch locked the slabs together and did not allow for movement caused by thermal and moisture changes in addition to loading (Buch, Vongchusiri, Meeker, Kaenvit, Command, & Ardani, 2005). After the Dulles installation a stitch that allowed for expansion/contraction was developed. Wiss, Janney, Elstner Associates designed a large-scale test procedure for the fiberglass insert and a traditional steel dowel retrofit. Static lab testing found the fiberglass insert had an ultimate strength of 21,360 lbs while the steel dowel's strength was 8,605 lbs. (Farriongton, Rovesti, Steiner, & Switzer, 2004) Fiberglass eliminated the corrosion of load transfer devices. Due to the thin, deep section it can be installed faster than a dowel retrofit. The second component is the use of expanding high-density polyurethane foam to raise the panel into place and provide full contact between the slab and the subgrade. This reduced time by eliminating the leveling/subgrade preparation. This method, particularly the fiberglass stitch, has since been discontinued.

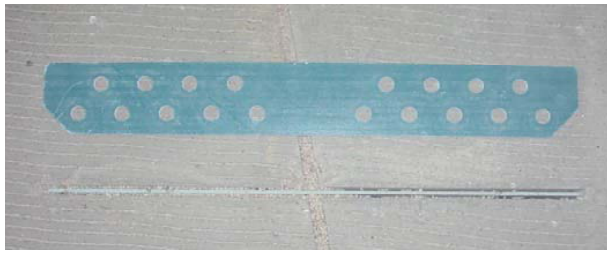


Figure 22 - URETEK Fiberglass Stitch

4.2.3 Kwik Slab (discontinued) and AE Connectors System

The Kwik Slab system was a proprietary system used on roadways since 2005 that simulates jointed reinforced concrete pavement (JRCP) sections. Use was limited to a small number of projects in Hawaii (Tayabji, Buch, & Kohler, 2008). It is often cited in precast papers as but is no longer produced. It used Kwik Joint Steel Couplers, in the reinforced slab, to quickly connect slabs together as seen below in Figure 23 (Kwik Slab, 2006). This enabled continuity of load throughout all sections. Due to this continuous connection the number of consecutive panels is limited. Kwik connectors were discontinued and replaced with a new connector system called AE Connectors.

Dr. Alfred A. Yee of Yee Precast Design Group Ltd. in Honolulu, Hawaii designed the connectors. It is a mechanical connector (splice) that consists of a collar around two deformed reinforcement bars that is filled with a high strength grout compound (Figure 24). They are used both in vertical precast and horizontal precast slab construction. The connector is slid onto one slab's exposed rebar and pushed to the rear of the slot. The next slab with associated rebar is placed and the AE Connector is pushed forward splicing the two rebar together. This is repeated for each strand of rebar. Then the high strength grout is mixed and injected into one of the ports on each connector (top right, Figure 24). Grout is also used to fill the rebar slots across the transverse length of each slab. Due to the connection, the pavement system acts as a continuously reinforced system, which has limitations on length due to thermal expansion of the material. At the time of publication, no further information was provided for expansion joints. This system has not been used on airfields or highways to date.

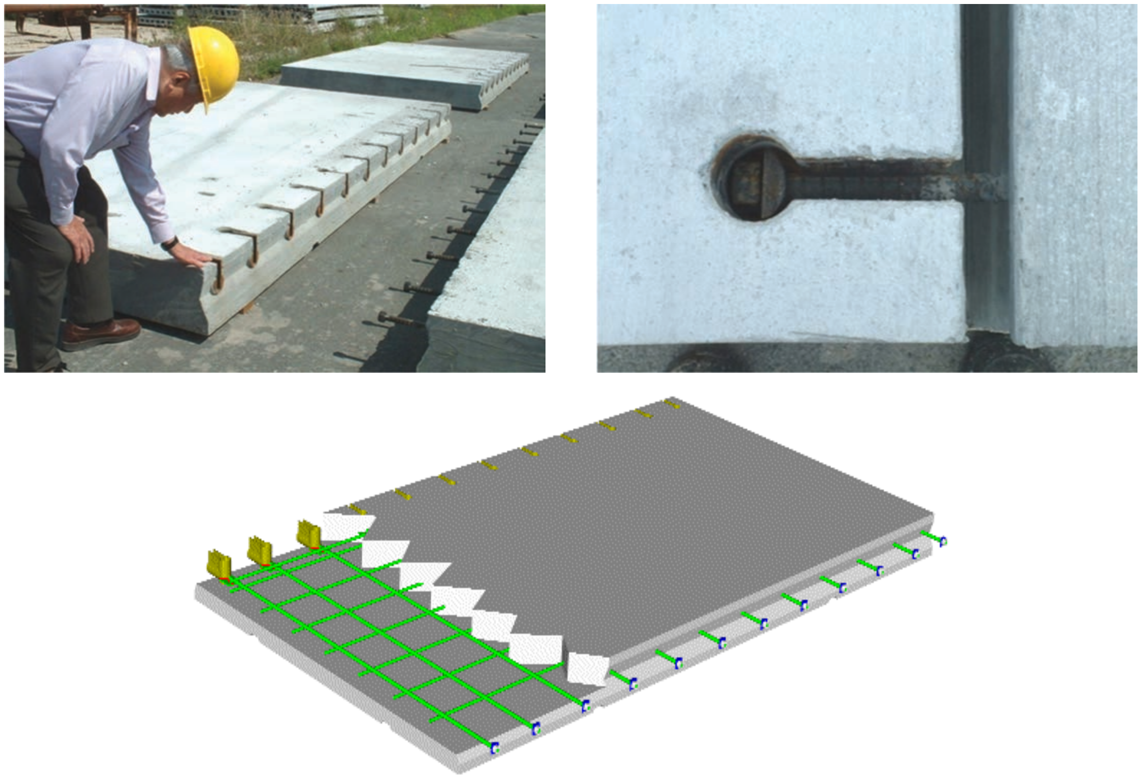


Figure 23 - Kwik Slab Precast Slabs and Kwik Joint Steel Couplers
(Kwik Slab, 2006; Tayabji, Buch, & Kohler, 2008)

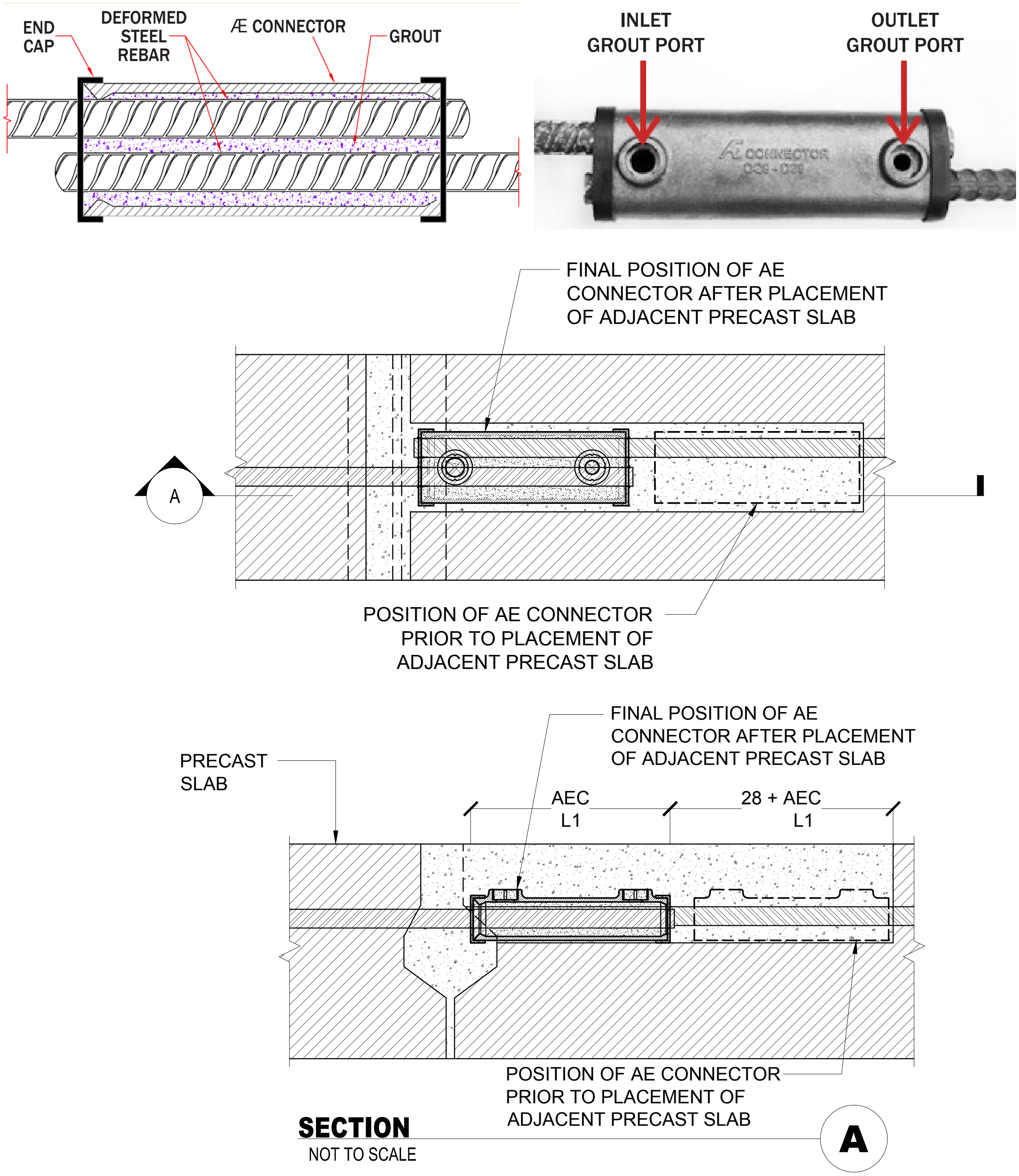


Figure 24 - AE Connectors Drawing
(AE Connector Solutions, PTE. LTD., 2015)

4.2.4 Barra Glide Slab System

The Barra Glide system is a proprietary PCP system by Rapid Roadway developed in 2013. The development was a collaboration between a contractor, concrete pavement expert and a grout supplier. The intent was to improve on existing systems used by the California Department of Transportation. A majority of work has been performed in southern California with a few highway projects elsewhere. The panels are placed on a lean concrete base over the existing subgrade. There are four proprietary components to this roadway system; the Gracie Leveling Lift™, the Barra Glide™ Load Transfer System, Performance Plus™ Bedding and Fill Grouts and Grout Containment™ (Rapid Roadway, 2015).

The Gracie Leveling Lift™ is dual purpose, serving as the lift anchor for panel movement and the leveling screw for the in-place panel (including superelevation) as seen below in Figure 25. The Barra GlideTM Load Transfer System is a center of the slab dowel bar slot with a narrow slit opening at the top of the slab used to push the dowel bar into the adjacent slab as seen in Figure 26. This slit and another grout hole is used to fill the opening once the bar is slid into place. Prior to slab placement a Grout Containment™ is placed on the prepared subgrade as both a bond breaker and to ensure the grout doesn't migrate to the adjacent slabs (Figure 27). The slab is under-sealed with a Performance Plus™ Bedding grout, which is rapid hardening, non-shrink, and sand-aggregate free, cementitious grout with the ability to flow into the small voids under the slab to establish full contact. The dowel slots are filled with a Performance Plus™ Fill grout with similar properties with the addition of sand (Rapid Roadway, 2015).

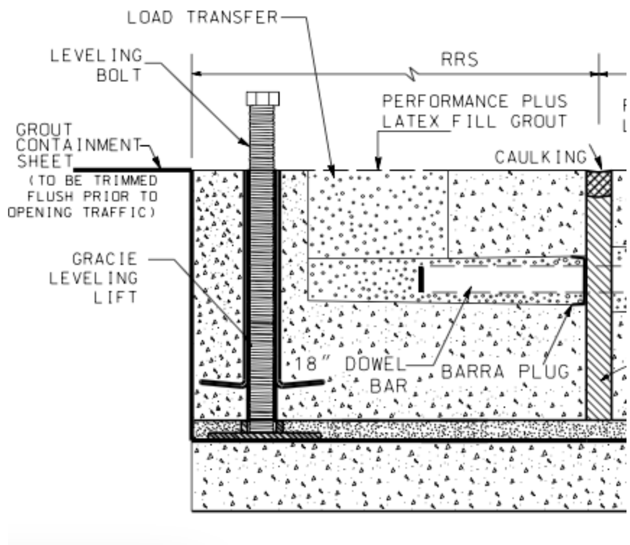


Figure 25 - Gracie Leveling Lift System Detail

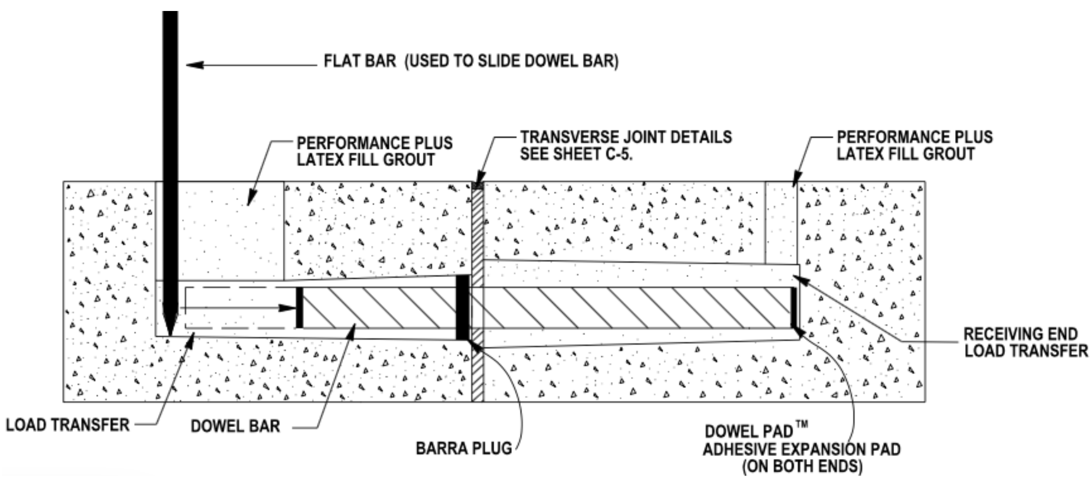


Figure 26 - Barra Glide Detail

Figure 27 - Grout Containment Sheet

4.2.5 ModieSlab System

ModieSlab is a proprietary system designed in the Netherlands in 2001 as part of the Roads to the Future program. The roadway design was for 100 years. The Netherlands has many areas of weak soil and in order to overcome some this with the ModieSlab systems was designed as a bridge type structure. Precast pile foundations were driven into the soil and capped with precast beams. The pavement slabs were then placed on the precast beams. The slabs consist of a reinforced base concrete (12.25 inches) and topped with a two layer (2.75 in) porous concrete. The top surface layer is fine-grained porous mix to reduce tire noise/surface water and the second layer is a coarser-grained mix to remove water quickly to the edges. Advancements were made to include a load transfer system for a slab-on-grade approach where soils were stronger.

Figure 28 - ModieSlab System in the Netherlands

4.2.6 Roman Road System

Roman Stone Construction Company developed the proprietary Roman Road System in 2009. This slab is cast whole (no dowel slots or dowels) and placed on a minimally prepared subgrade. Typically the slab is one inch less deep than the existing pavement. The one-inch difference is made up through the use of URETEK's high-density polyurethane foam, which raises and levels the slab while ensuring complete contact between the slab and the subgrade. After the foam is injected, dowel slots are cut into the precast and existing slabs. The dowel bars are then placed and subsequently grouted (Roman Stone Construction Company, 2014).

Figure 29 - Roman Road System Installation (left) and URETEK Underslab Grouting (right)

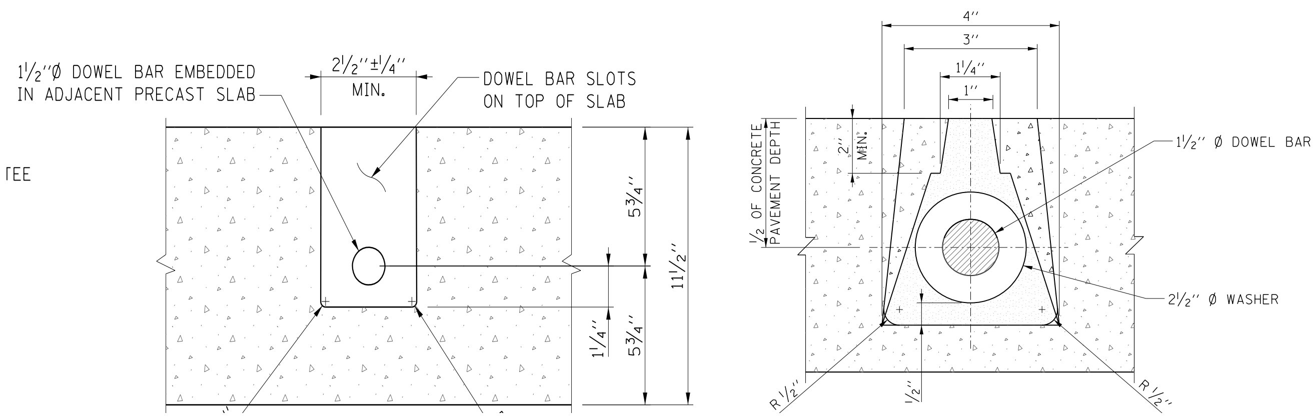
4.2.7 Generic Slab Systems

Due to procurement policies at various agencies, it can be difficult to sole-source a company or product. Therefore, a need has developed for non-proprietary systems, which enable agencies to utilize and enhance bid competition between precast pavement products (Tayabji, Ye, & Buch, 2013). A few systems are discussed below.

4.2.7.1 Illinois Tollway Narrow Mouth Surface Slot Panels

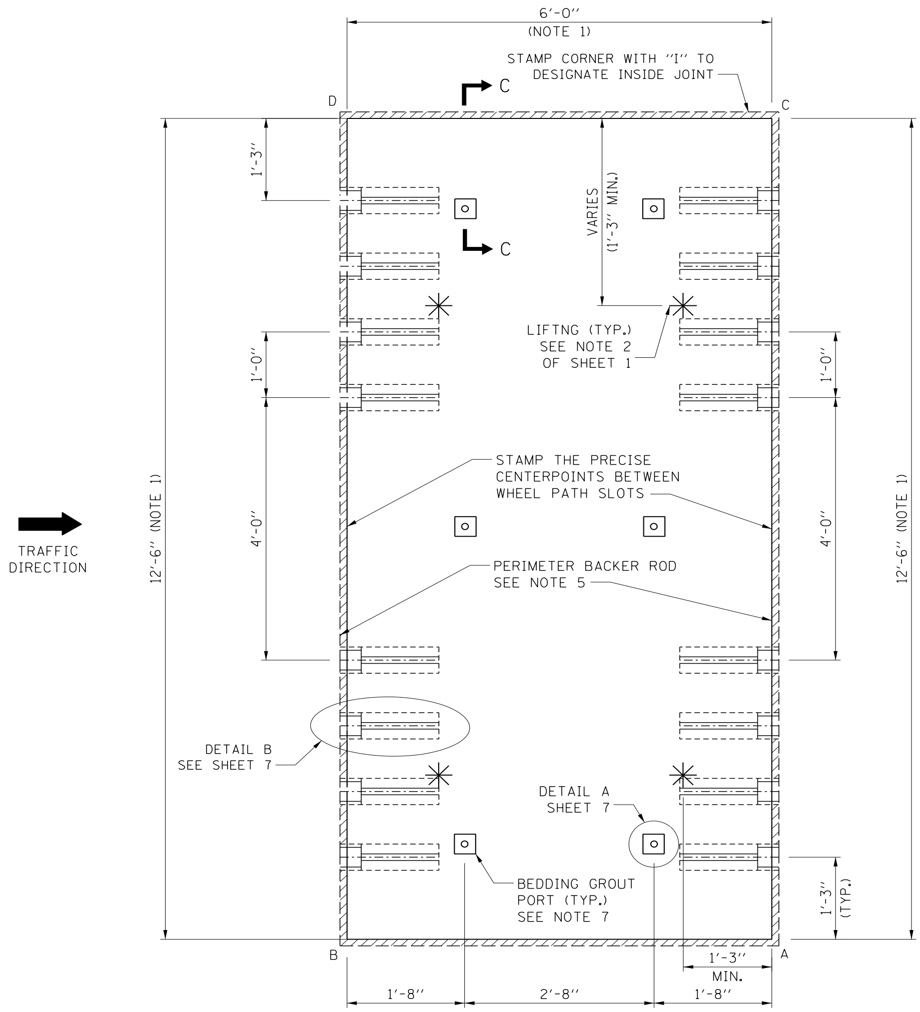
This is a non-proprietary system used by the Illinois Tollway. Traditional dowel slots, such as those used for dowel bar replacement (two and a half – three inches wide), have a uniform width with respect to depth and because of the width they must be grouted before opening to traffic. In contrast, the narrow mouth surface slot opening is about one inch tapering out to three inches at the bottom. This smaller surface width allows opening the road for traffic without grouting. It is common for the slot to open wider at the joint face to allow for easier installation and the twisting of the epoxied dowel bar. Generic cross sections for wide and narrow mouth and a standard panel drawing are seen in **Figure 30 (cont.)**a,b,c, (Illinois Tollway , 2015). Another advantage of the Illinois Tollway system is the mechanical interlock achieved by the tapered design between the precast concrete and the dowel slot grout.

Installation is similar to other systems. These panels are placed on a fine aggregate bedding layer. The epoxy-coated dowel bar is epoxied pushed into the adjacent slab and the slots are grouted. The entire slab is under-sealed with a high flow grout to fill remaining voids and establish uniform contact for load transfer between the slab and the subgrade. A backer rod is placed under the slab to ensure grout does not fill the joints or enter beneath the adjacent slab. An alternative bedding method is a flowable fill. The Illinois Tollway has used this technique throughout northern Illinois network with great success since 2009 (Gillen, 2015).



a) Wide mouth section view **b) Narrow mouth section view**

Figure 30 - Illinois Tollway Precast Panel Design



c) Plan view

Figure 30 (cont.)

4.2.7.2 Michigan Method

The Michigan DOT developed this method. The method casts three dowel bars into each wheel path for a total of 12 bars per slab. The existing slab is cut to provide a receptacle for the PCP and dowel bars. Perimeter reinforcement is used to resist handling and transportation stresses. At slab mid-depth, a steel mesh (0.375 inch diameter) is placed every six inches to resist the potential of early age cracking (Buch N. , 2007). Slab bedding has been done via flowable cementitious grout and high-density polyurethane foam. Installation is similar to other systems.

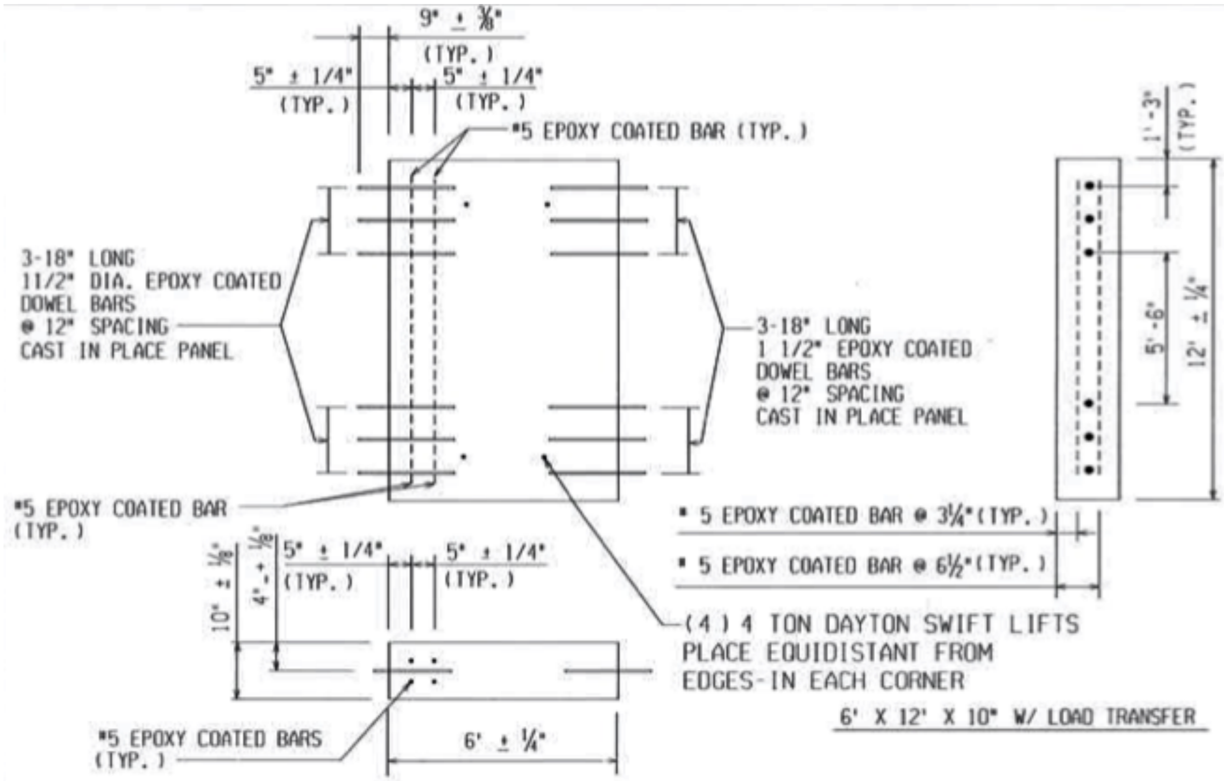


Figure 31 - Michigan Method Precast Drawing

4.3 Precast Concrete Panel Airport Testing

A joint venture between the Air Force Research Laboratory (AFRL) and US Army Engineer Research and Development Center (ERDC) was conducted to evaluate PCP as a repair method used in contingency environments. The need for rapid pavement repair in contingency environment is critical for mission generation after pavement damage. Although rapid repair materials may be used, often they are logistically challenging to move and may not be available in sufficient quantities in all locations. Typically these quantities use for small repair projects to provide a minimum operating strip. PCP optimization/construction and full scale accelerated testing with instrumentation (strain gauges and pressure cells) was loaded by a C-17 loadcart in Vicksburg, MS. The process and results were published in two phases. (Bly, Priddy, Mason, & Jackson, 2013; Priddy L. P., Bly, Brogdon, & Jackson, 2013).

4.3.1 Accelerated Testing Setup

Full scale testing was performed for three different repair types. These types consisted of a single panel, double panel and quad panel repair. This simulated a quarter (P1), half (P2/P3) and full (P4/P5/P6/7) panel replacement as seen in Figure 32. The test section was design using Pavement-Transportation Computer Assisted Structural Engineering (PCASE) software. Critical inputs include design life of 50,000 passes of a C-17, six inch aggregate base, subgrade k-value of 150 lbs/in^3 and a flexural strength of 650 psi. Based on the software recommendations a 20-foot panel by 14 inches deep was selected with 20 inch long by one inch diameter dowels, spaced at 15 inches on center. The repair panels were 10 feet square by 11 inches deep. Three inches of aggregate base was added to account for the three-inch difference during the repair. The test section with completed repairs is seen in Figure 33.

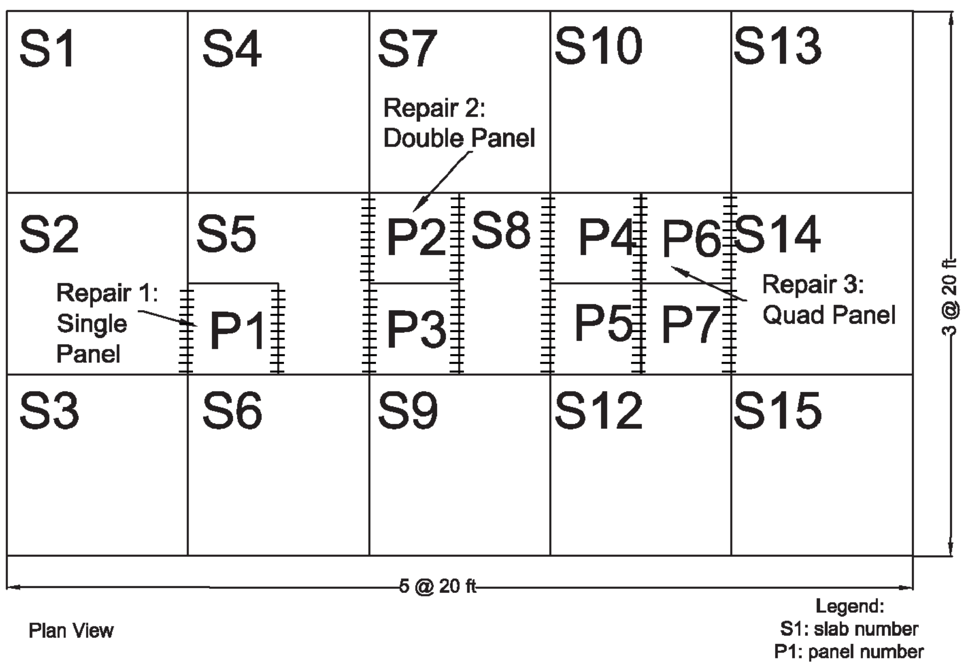


Figure 32 – U.S. Army ERDC Full Scale Test Section Layout

Figure 33 - U.S. Army ERDC Completed Precast Panel Repair

4.3.2 Accelerated Testing Results

After repairs were completed the sections were loaded with a C-17 load cart, which simulates one belly gear set. The load cart simulated the max weight of a C-17 (586,000 lbs), which equates to a test weight of 269,560 lbs. Individual wheel loads were approximately 44,930 lbs with tire pressures of 138 – 144 psi. The pavement was trafficked until 10,000 passes or pavement failure. The wheel paths were performed using a normal distribution. In addition to strain gauges and pressure cells, faulting and heavy-weight deflectometer (HWD) testing was performed throughout testing.

Figure 34 - C-17 Load Cart

After different load levels were applied, each repair section failed. For the quarter slab repair, after 5,600 passes were applied the original and precast panel failed because of a high-severity shattered slabs. For the half slab repair, 10,000 passes were applied before failure be of high-severity joint spalls and deterioration of the dowel slots of the existing slab. The full slab precast panel failed after 7,100 passes because of high-severity joint spalling of the original and precast repair panel.

a)

b)

c)

d)

Figure 35 – U.S. Army ERDC PCP Accelerated Testing Damage:
a) Repair 1- high-severity corner break/spalling with a shattered parent slab, **b)** Repair 2 -diagonal crack in parent slab between Repair 1 and 2 with cracking/spalling of Panel 2 from parent slab deterioration, **c)** Repair 2 - close-up of cracking/spalling of Panel 2 due to parent slab deterioration, **d)** Repair 3 - Panels 6/7 with high-severity spalling at corners of repair and parent slab

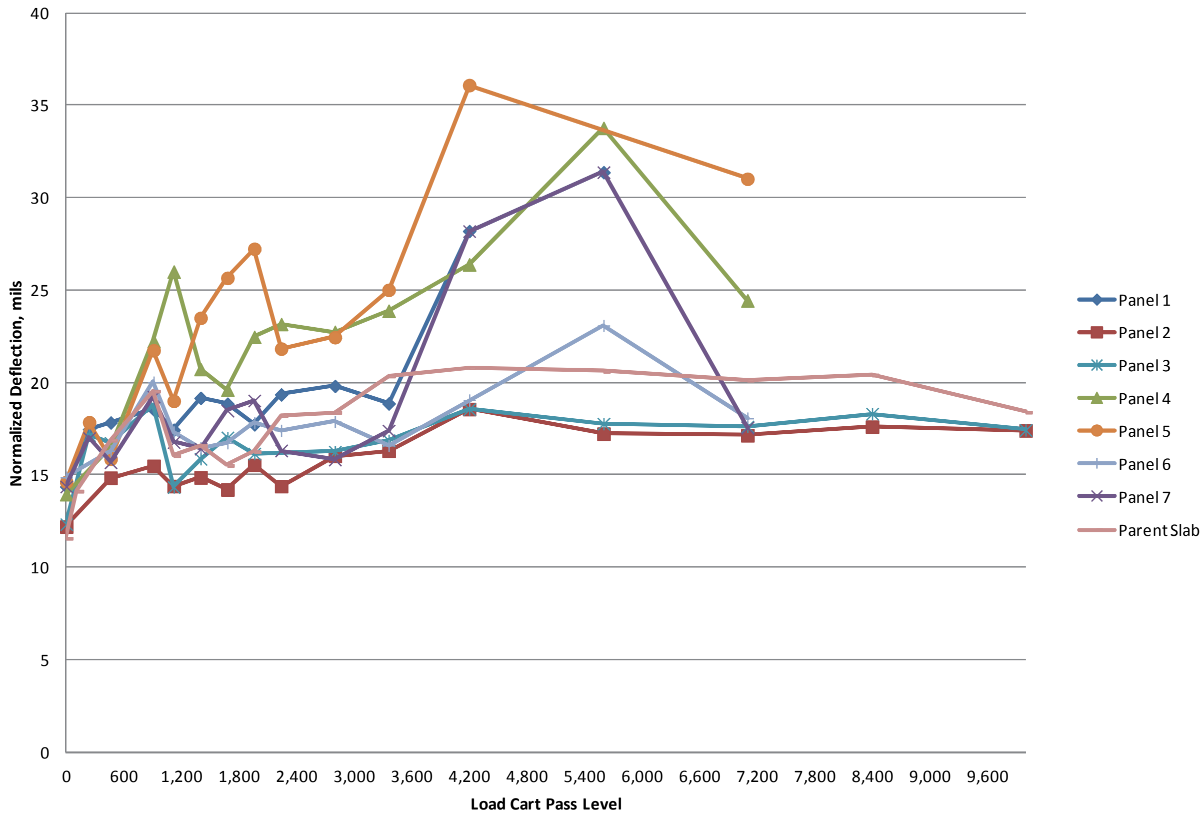
The additional roughness from faulting after loading was minimal. The maximum elevation change between adjacent panels at the end of testing was 0.375 inches. After construction, no diamond grinding was performed, which is typically standard practice to achieve a smooth and textured surface. These elevation changes varied and were not remedied prior to loading. There were 6 out of 56 measurement locations had with a half-inch elevation change between slabs. The largest final faulting value was 0.625 inches, which is substantially less than the three-inch maximum criteria for C-17 aircraft.

HWD testing was performed using a 12-inch plate and loads from 39,000 to 57,500 lbs. Measurements were taken to backcalculate layer moduli, load transfer efficiency (LTE) and the decay in stiffness with repeated trafficking. The dynamic cone penetrometer (DCP) was used to determine the California Bearing Ratio (CBR) for the aggregate base and subgrade. The modulus was estimated based on CBR values multiplied by 1500. As seen in Table 9 the parent slabs showed little reduction in modulus values throughout the pavement structure. A significant reduction was seen in the PCP pavement structure. This was attributed the panel cracking as well as the cracking of the flowable fill material.

Table 9 – U.S. Army ERDC HWD and DCP Moduli Values

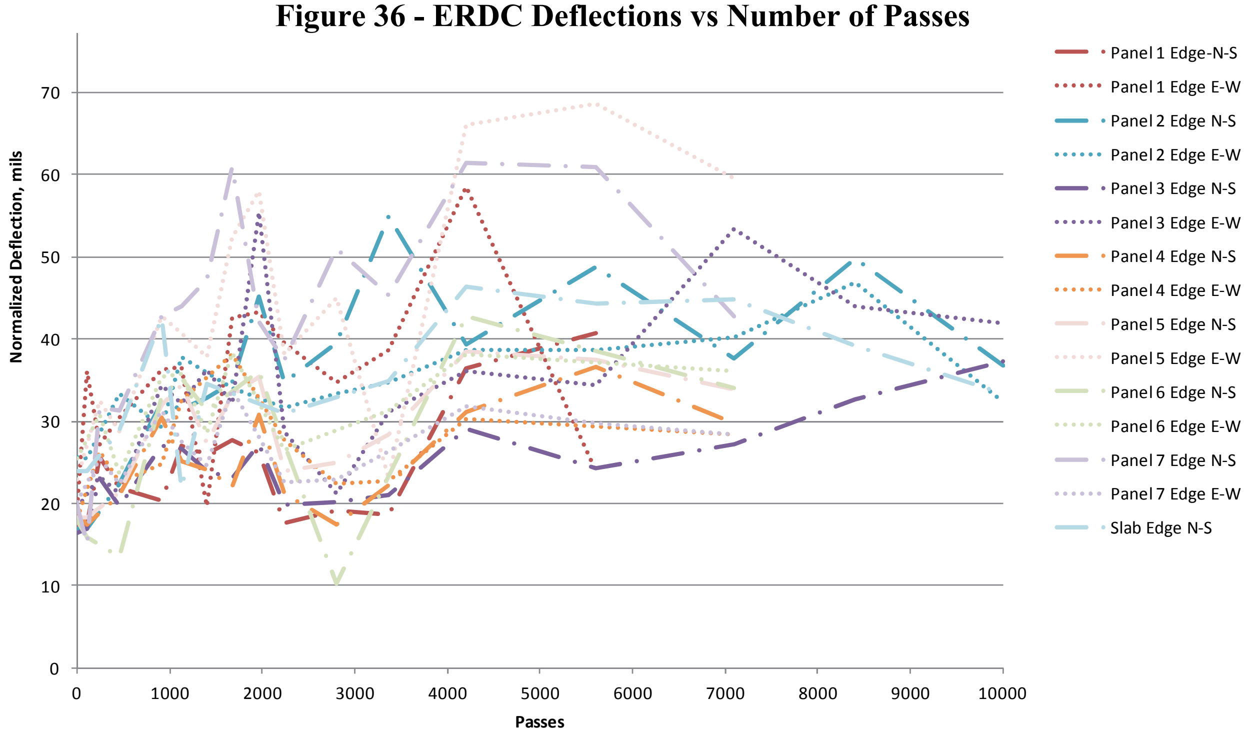
Test	PCC Modulus (psi)	Backcalculated HWD		DCP-Estimated	
		Base Modulus (psi)	Subgrade Modulus (psi)	Base Modulus (psi)	Subgrade Modulus (psi)
Pre-repair slabs	5,000,000	49,276	24,453	55,000	21,000
Post-traffic slabs	5,000,000	48,333	23,737	55,000	21,000
Pre-repair panels	6,248,706	54,892	24,453	n/a	n/a
Post-traffic panels	2,545,719	33,488	11,560	n/a	n/a

The center, edge and corner slab deflections increased with traffic. Figure 36 shows this generally increasing deflection trend for all panels. Panel 1, 4, 5, and 7 showed the highest deflections. The half slab repair had the lowest recorded deflections. The highest center, edge and corner deflections (pre-traffic/post traffic) were 15/36 mils, 17/68 and 20/71 mils, respectively.

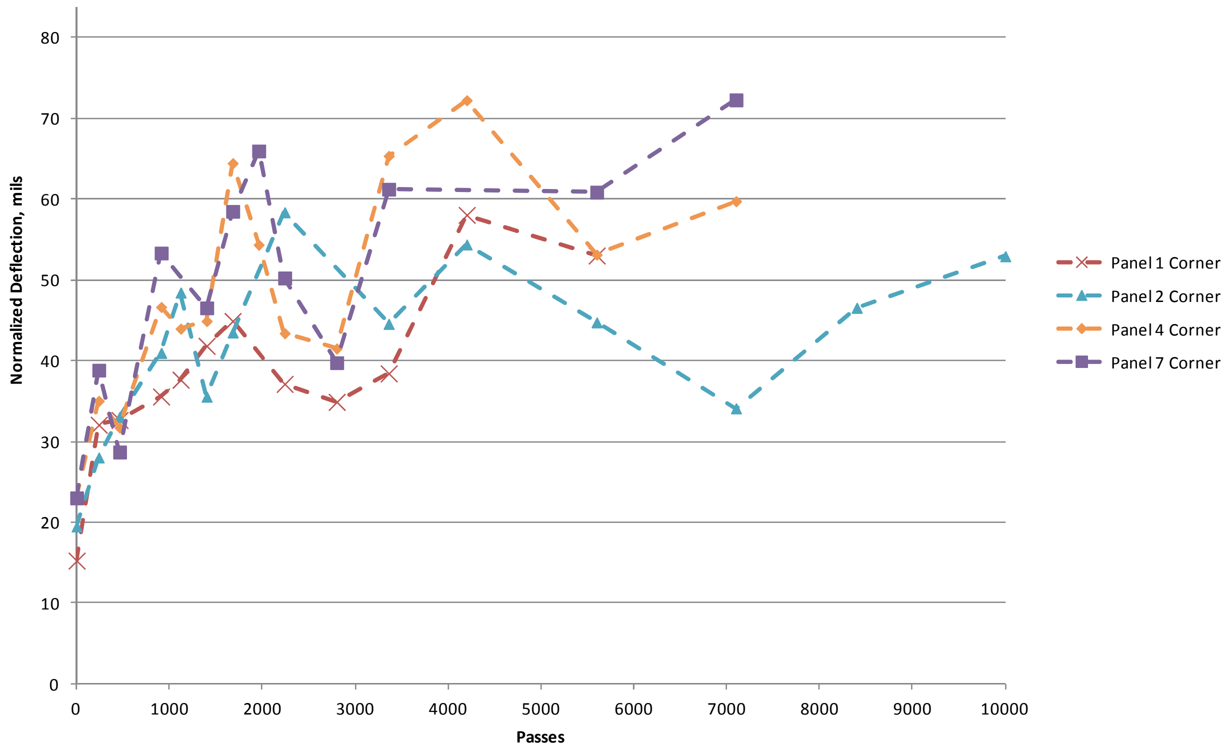


a) center slab

Figure 36 - ERDC Deflections vs Number of Passes



b) edge slab



c) corner slab

Figure 36 (cont.)

LTE values decreased with trafficking as seen in Table 10. The undoweled, longitudinal joints had significantly lower LTE than doweled joints as expected.

Table 10 – ERDC LTE Values for Various Locations

Panel	Norht Joint Start LTE	Norht Joint Final LTE	South Joint Start LTE	South Joint Final LTE	East Joint Start LTE	East Joint Final LTE	West Joint Start LTE	West Joint Final LTE
Panel 1	91	74	93	76	89	20	88	77
Panel 2	91	79	97	61	54	85	79	50
Panel 3	92	50	90	85	-	-	63	81
Panel 4	94	92	90	88	94	32	68	12
Panel 5	92	70	94	79	-	-	56	40
Panel 6	-	-	93	84	44	27	63	19
Panel 7	-	-	94	59	-	-	72	32

Four of seven pressure cells were damaged during loading. However, the remaining cells provided data throughout the testing. Figure 37 shows the pressure remained fairly constant throughout loading. Center slab pressures ranged from 3.5 – 6 psi while corner slab pressures were 9 – 10 psi. Many surface strain gauges were damages under initial loading and therefore provided limited data. Figure 38 shows strains at various locations for Panels 5 and 6. Generally, strains increased with traffic repetitions.

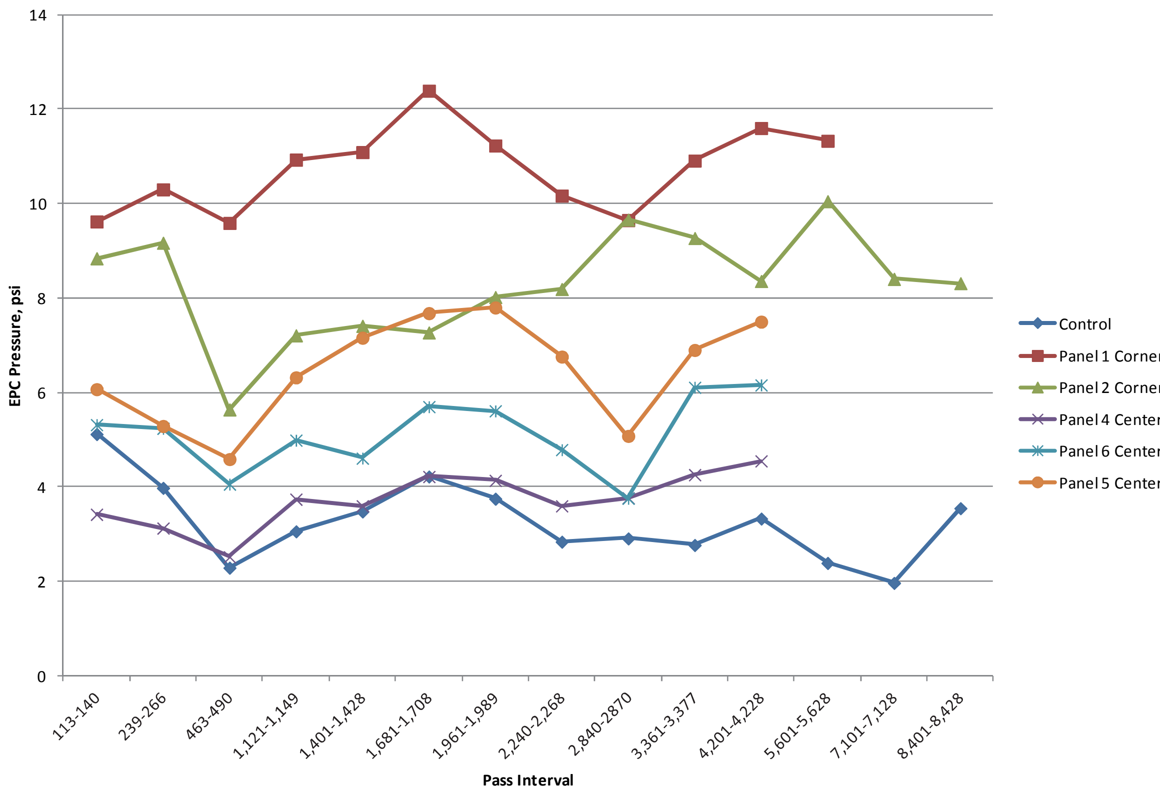


Figure 37 – Peak Pressure Measurements

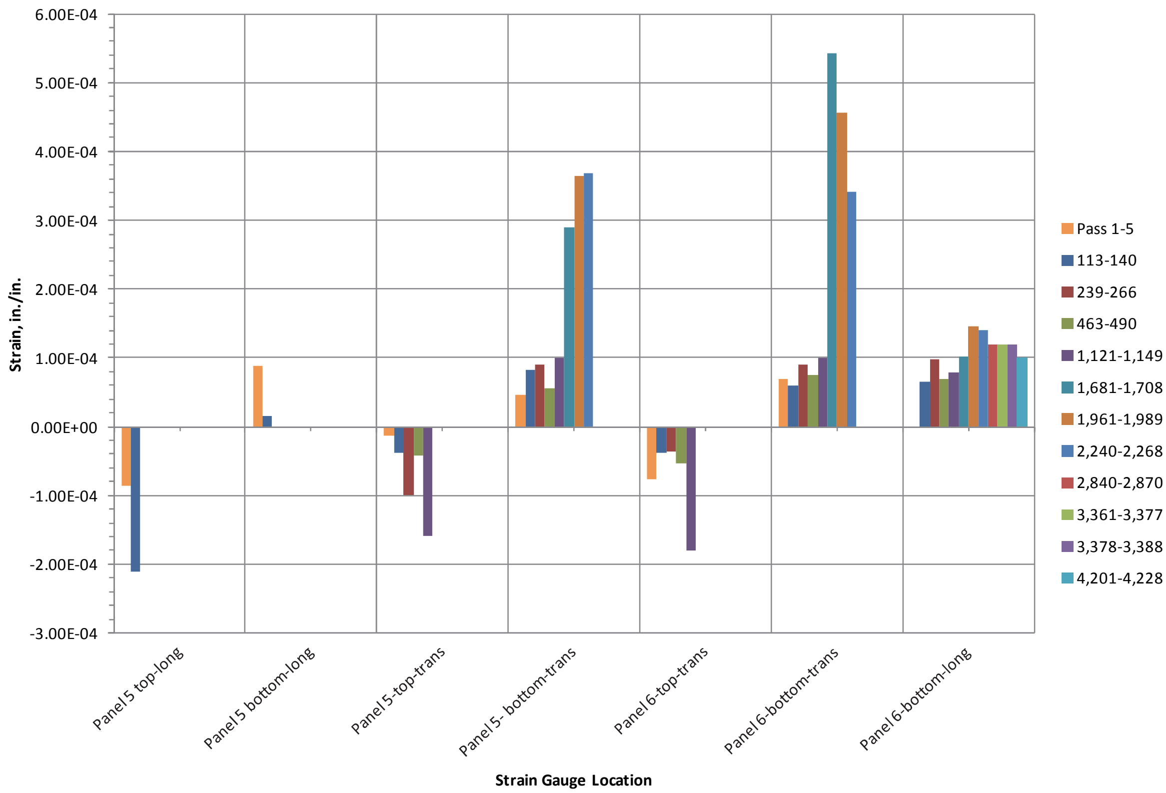


Figure 38 – ERDC Peak Strain Measurements

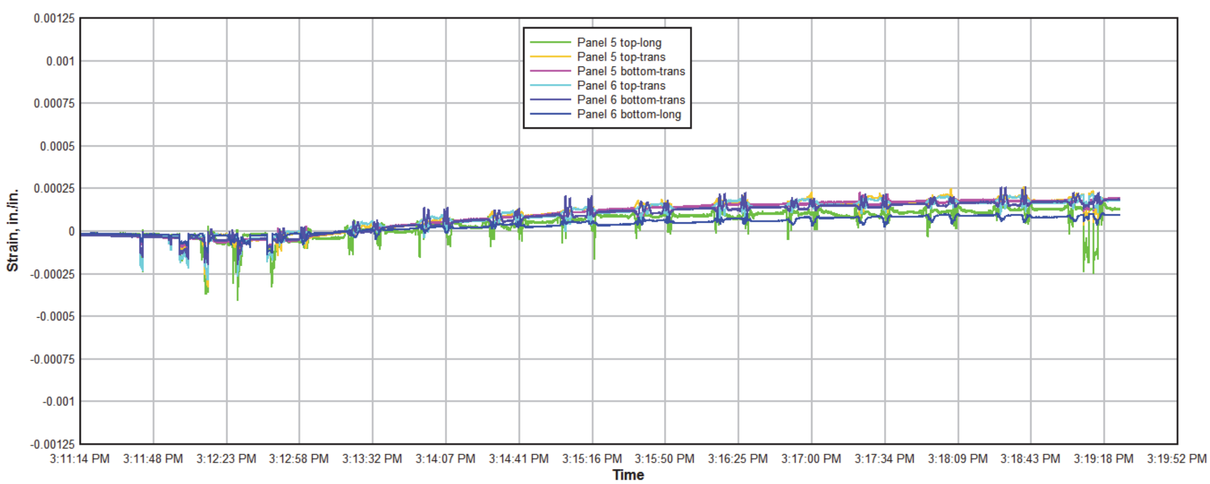


Figure 39 – ERDC Edge Strain Measurements for Panels 5 and 6 (passes 463-490)

Based on rapid airfield repair criteria (5,000 passes of a C-17) these panels met and exceed the requirements. ERDC deemed this to be a viable repair method, which was about 34% more expensive than a rapid setting material (Priddy L. P., Bly, Brogdon, & Jackson, 2013). Further testing should be performed to increase the life. For example, changing the slab design to utilize a gang drill on the parent slabs as opposed to a dowel retrofit may extend the life and reduce FOD generation. This would also simplify the PCP construction process by eliminating dowel placement/removal and would rely on block-outs on the underside of the slab. Additionally, testing should be completed on thicker pavement sections, which would be more realistic to airfields. An 11 – 14 inch panel resembles interstate pavements. They deflections and loadings would change as pavements depths range from 18 – 21 inches. Understanding the failures using different type of PCP bedding would allow for greater optimization.

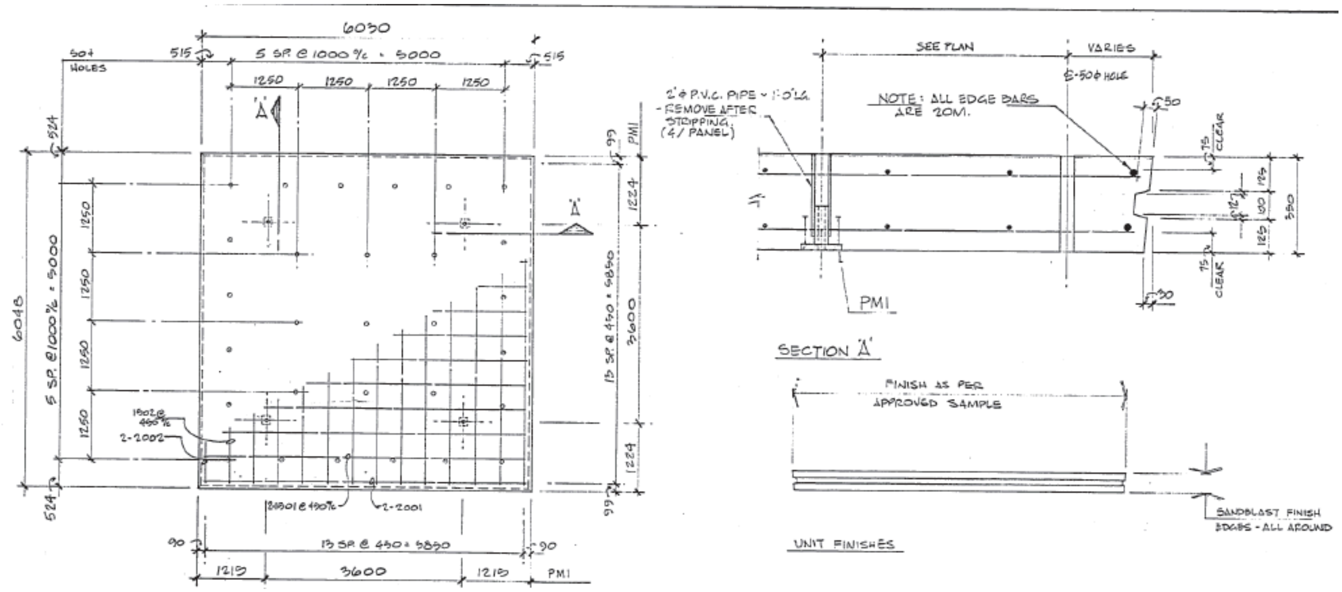
4.4 Precast Concrete Panel Use in Airports

Precast pavements in airports have been used in Europe, Japan and the United States since the 1940s (Rollings & Cho, 1981). In the past 20 years PCPs test sections have been demonstrated at four airport locations; Calgary International, Dulles International, La Guardia International and Lambert-St. Louis International. Further material is presented later on each specific airport. Other airports have used PCPs for temporary surfaces during construction activities (Figure 40). These include Seattle-Tacoma International, Charleston International and Savannah/Hilton Head International airports. PCPs were used to increase production by allowing a larger section to be removed in a night while opening to traffic the following day. The next night, the PCPs were removed and the designated PCC mix was poured. It also allowed for emergency measures if equipment broke down or an early opening of the runway was required (Peshkin, Bruinsma, Wade, & Delatte, 2006).

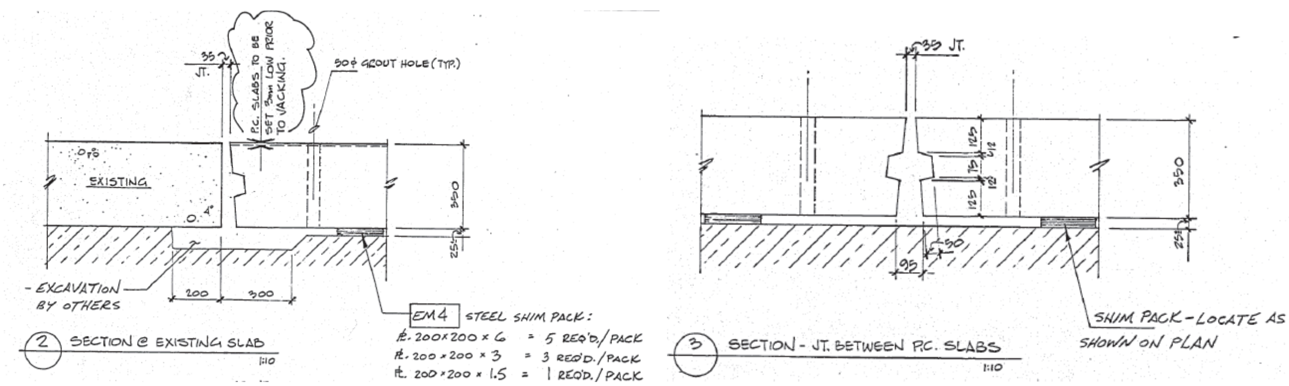
Figure 40 – Temporary PCP Used at Savannah-Hilton Head International Airport
(Peshkin, Bruinsma, Wade, & Delatte, 2006)

4.4.1 Calgary International Airport's Use of Precast Concrete Panels – 1990's

Calgary installed 13 trial panels in the early 1990's. The existing slabs were 20 ft x 20 ft x 14.75 inches thick, on six inches of soil cement, on two inches of asphalt, on 8.66 inches of granular material over a compacted subgrade. The repair panel dimensions were of varying sizes (largest was a 20 ft panel) pending the distress repaired with thickness of 13.75 inches. The reinforcement consisted of a top and bottom mesh (three inches from surface) of #5 bar (0.625 inch diameter) with a #6 (0.75 inch diameter) edge bar (Figure 41a). The pavements were placed on steel shims and the void (approximately one inch) under the slab was grouted after placement. The panels had a modified key joint as seen in Figure 41b with a bond breaker applied to the side face of the precast panel. For ease of installation the slabs were produced to be more than one inch smaller than the existing slab.



a) Calgary PCP reinforcement drawing



b) Calgary PCP joint drawing

Figure 41 - Calgary Precast Panel Drawings

Figure 42, taken in 2007 shows one of these panels. In 2010, Mr. Jim Lightfoot reported that 10 of 13 panes were still performing well with no evidence of cracking. The panel shown in Figure 42a, was removed in 2013 during annual maintenance due to cracking in the surrounding panels. Figure 42b, was the panels condition prior to removal. Figure 42c, shows the current condition of a panel installed in the same time frame. It is in good condition for over 20 years with a minor corner spall (Botero, 2015).

a) 2007 condition (12-15 yrs)

b) 2013 condition (18-21 yrs)

c) 2015 condition of other PCP in same area (20-22 yrs)

Figure 42 – Precast Slab Replacement at Calgary International Airport
(Lightfoot, 2007; Botero, 2015)

4.4.2 Lambert-St. Louis International Airport's Use of Precast Concrete Panel

Runway 12L/30R was deteriorating in the late 1990s and was in in need of a rehabilitation by 2000 – 2002. In 1998 solutions were evaluated on how to extend the RW life until RW 12R/30L could be opened in 2006. The original RW was constructed in 1961 as 14-inch PCC pavement. In 1980 a 10 inch partially bonded PCC overlay was constructed. Additionally, the project included a 3,000 foot x 150 foot extension from 16 inches of PCC (Crawford, Murphy and Tilly, Inc., 2000). Two test sections were constructed; one using rapid set and the other using a PCP. Though both proved successful for weekend closures, because of changes in aircraft operations, the selected rehab for the entire keel section was a full depth reconstruction (Sander & Roesler, 2006).

For the PCP panel, the specific replacement site consisted of 11 inches of PCC on 2 inches of AC on 14 inches of PCC. The precast panel was cast in two pre-stressed pieces (12.5 feet x 25 feet x 11 inches). This particular installation was not completed in a consecutive time period, as it was a demonstration of the methods and a learning experience to make future repairs smoother. On day one, a cold milling machine was used to removed 10 inches of PCC but it left one foot on each side due to the dowel bars which were saw cut and removed after milling. Due to damage from the milling machine, the two inches of asphalt was also removed. The final cleanout occurred on day two. On day three the panels were delivered and were post-tensioned together as one panel. The panel was tensioned and set on the leveling beams. The grouting was changed from a rapid set cement to a conventional cement because of problems pouring (concrete set in truck) the rapid set cement on the previous rapid repair test panel. A conventional bedding grout was poured, the panel was placed and then a vibratory roller ensured the panel was seated. After approximately two hours the TW was opened to traffic.

Table 11 – St. Louis PCP Construction Activities

Major Activities	Install Time (hrs)
Milling Begins	0800
Edge Breakout Start	1030
Edge Breakout Completed	1120
Day 2	
Clean Out Start	0700
Clean Out Complete	0815
Day 3 (Not a critical path item. Tensioning can be done offsite)	
Panels Arrive and Assembly Begins	1045
Tensioning of Panels	1235
Practice Lift Started	1415
Grouting of Tensioning Tubes	1500
Grouting Complete	1730
Day 4	
Mobilization for Panel Placement	0400
Grout Start	0622
Panel Install Start	0640
Panel Set/Vibratory Roller Start	0645
Finish Grouting Completed	0815
Opened For Traffic	1015
Total Time (hrs)	**14**

4.4.3 Dulles International Airport's Use of Precast Concrete Panels 2001 & 2002

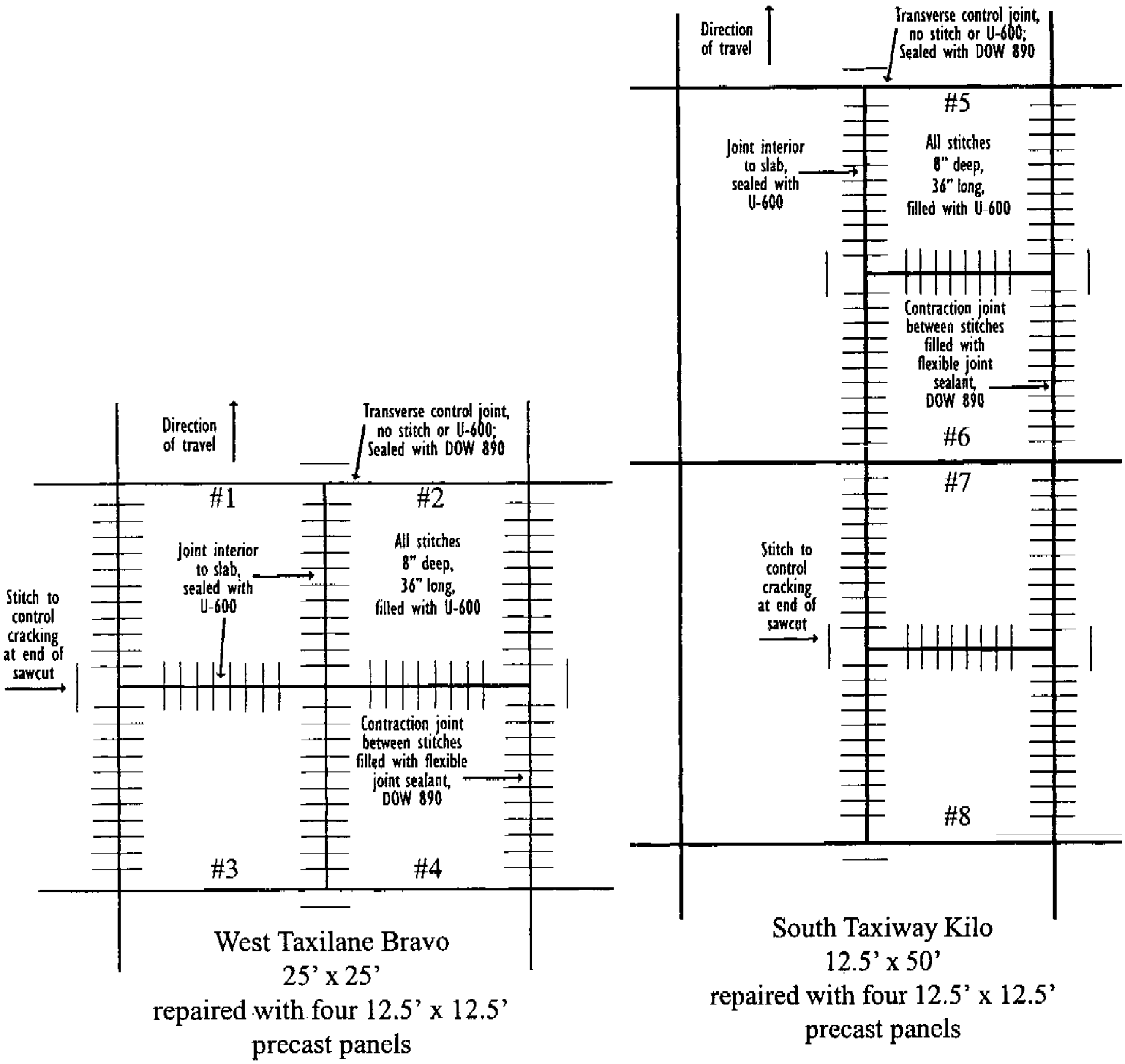
Dulles International tested two different methods, URETEK Stitch-in-Time and Fort Miller Superslab system in 2001 and 2002, respectively. Due to maintenance access and closure issues these new repair methods were used to determine their feasibility. The repair was to be used for five – ten years after which a complete rehabilitation/reconstruction would be performed. Both systems met the project goals and intent as discussed below.

4.4.3.1 Dulles International Airport – URETEK Stitch-in-Time Method – 2001

The Stitch-in-Time method was previously used in highway overnight applications but Dulles was the first, and only, to use it on airfields. As discussed previously, the fiberglass dowels are no longer used but the high-density polyurethane foam is used to fill voids and raise slabs (Crowley, 2015). For completeness the PCP installation at Dulles is presented. The replacement 98 yds^2 of 15-inch thick pavement with longitudinal and transvers dowels originally installed in 1962. One 25-foot panel was on West Taxilane Bravo and two consecutive half-panels (13 ft x 20 ft) were on South Taxiway Kilo (Figure 43). Taxilane Bravo repair panels dimensions were 12.5 feet x 12.5 ft x 14 inches and Taxiway Kilo repair panels dimensions were 6.5 feet x 10 feet x 14 inches. These panels had two mats of #4 steel bars, 12 inches on center. The stitches were placed at one foot on center around all PCP edges with the exception of the transverse joint of the existing concrete. This was done to replicate the old doweled panels. With the stitch-in-time product, all joints were locked and limited movement occurred (Farriongton, Rovesti, Steiner, & Switzer, 2004).

The construction timeline varied over the six nights. Exact time measurements for each activity were not provided. In general, the work for two slabs started around 2300 hours, pending actual closure time. The removal process took about four hours and the foam injection started about 0300 hours and ended at 0530 hours. The site was cleaned and opened to traffic at 0600 hours. The slot stitch and installation was conducted on subsequent nights. Rainwater did cause a slow-down in the installation of the stiches but there was no impact to operations (Farriongton, Rovesti, Steiner, & Switzer, 2004).

Initially, these repairs were a mid-term solution until a larger project would provide a full rehabilitation. The PCP repairs extended the design life showing the vitality of this repair. Figure 44 shows the condition of Taxilane Bravo in 2013. The PCP panels themselves are in good condition indicating good durability. However, the joints that were locked together with the stitches have evidence of failure based on the asphalt patching repairs seen along several joints.



a) West Taxilane Bravo **b) SouthTaxiway Kilo**

Figure 43 - Dulles PCP Repair Layout
(Farriongton, Rovesti, Steiner, & Switzer, 2004)

Figure 44 - Dulles Taxilane Bravo Stitch-in-Time Method Condition in 2013
(Thuma, 2013)

4.4.3.2 Dulles International Airport – Fort Miller SuperSlab Method - 2002

This method was used to replace 389 yd^2 of 15-inch thick pavement with longitudinal and transverse dowels originally installed in 1962. Four 25-foot panels selected for replacement were on Taxilane Bravo and another two panels (20 ft x 25 ft) were on Taxiway Yankee. The repair panel dimensions were limited by the ability to deliver the panels on public roads from the precast plant to the job site. Also, in order to maintain drainage (changed over the years because of panel movements) warped slabs were used. Taxilane Bravo panel dimensions were 12.5 feet x 25 feet x 13 inches and Taxiway Yankee panel dimensions were 12.5 feet x 20 feet x 13 inches. The reduction in thickness was to accommodate the granular fill-bedding layer of 1-2 inches. The panels were heavily reinforced to account for heavy loads, lack of load transfer and compensate for unknown subgrade conditions. The reinforcement also was placed to ensure crack control because of the high length-to-width slab size ratio. Dowels were installed between the new panels but not retrofitted into the existing adjacent slabs (Switzer, Fischer, Fuselier, Smith, & Verfuss, 2003).

Table 12 (adapted from Switzer, et al, 2003) shows the timeline for PCP installation. For Taxiline Bravo, the completion of the first two panels exceeded the nine-hour nighttime closure window by six and a half hours. There were issues in slab removal and installation measurements that set back the construction team. The two subsequent Bravo panels were completed in nine and a half hours and the two Taxiway Yankee panels were completed in eight and a half hours. This shows the steep learning curve of the new technologies and contractors not familiar with the process. It also shows the importance of a test run to work out the personnel and equipment allocations. The slab demolition and finish grading required substantial time. Currently, the technology and processes have improved over the past 15 years and are more efficient and familiar to contractors. For highways, production rates are as high as 475 – 600 yd^2 per eight-hour closure (Smith P. , 2015). Due to the larger size PCP for airports, larger equipment must be used to remove, haul away and install new slabs as seen in Figure 45. Also, consideration should be given to the distresses present in the slabs. Instead of lifting out in a monolithic piece, multiple pieces may need to be considered (Figure 45). Lifting anchor placement may vary. If the slab is shattered, other demolition equipment will be required to remove the pieces while limiting subgrade disturbance. Figure 46 shows the finished installation after the first night in 2002. This project, after the learning curve, met the project expectations as an acceptable rapid repair technique. While the initial design was for five to ten years, the pavement is still performing well after 13 years. Figure 47 shows the current in-service condition in 2015. A small corner patch is visible in one of the slabs. Small, tight cracks are see but are not concerning as they are held together by the steel reinforcement.

Table 12 - Timeline for Dulles PCP Installation

Major Activities	Planned Install Time (hrs)	Bravo 1 Panels Install Time (hrs)	Bravo 2 Panels Install Time (hrs)	Yankee Panels Install Time (hrs)
Slab Removal Begins	2200	2200	2200	2200
Bedding Placement Start	100	350	315	115
Finish Grading Start	200	445	400	310
Panel Placement Start	300	930	540	405
Completion/Open TW	500	1330	730	630
Contingency Completion	700	1330	730	630
Total Time (hrs)	**8**	**15.5**	**9.5**	**8.5**

Figure 45 - Dulles Slab Demolition
(Fischer, 2002)

Figure 46 - Dulles Taxiline Bravo PCP Completion
(Fischer, 2002)

Figure 47 - Dulles Taxilane Bravo PCP Condition
(Thurma, 2015)

4.4.4 La Guardia International Airport's Use of Precast Concrete Panel – 2002

The Port Authority of New York and New Jersey experience premature flexible pavement failures on the taxiways because of the fully loaded aircraft, stop-start movements. The Port Authority in these congested areas prefers the use of PCC in these congested areas. In 2002, the Port Authority placed two different PCP test sections (556 yd^2 each) at La Guardia during a 36-hour closure on Taxiway D-D (Chen, Murrell, & Larrazabal, 2004).

System A was a pre-tensioned precast panel and System B was a conventional precast panel. For System A (16 panels), a 12.5 foot x 25 foot x 12-inch thick slab was designed (light can forced a two inch increase in depth) with half-inch diameter pre-stressed steel strands spaced at 24 inches on center in each direction. A force of 47,000 lbs was applied to each strand providing an additional flexural strength of 150 psi for a total of 850 psi (concrete strength plus prestress). Dowel bar dimensions were 18 inches long with a 1.5-inch diameter and a spacing of 12 inches on center (Figure 48).

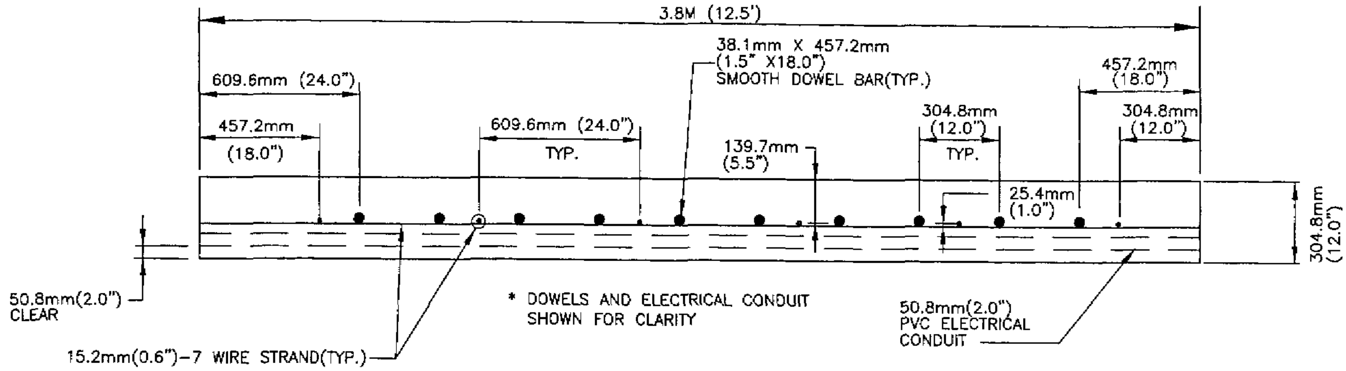


Figure 48 - La Guardia System A - PCP (Pre-stressed) Cross-Section
(Chen, Murrell, & Larrazabal, 2004)

System B (16 panels) was a 12.5 foot x 25 foot x 16-inch thick slab was designed with a top reinforcing mesh of #5 bars at 15 inches in each direction. This provided restraint against shrinkage cracking and crack control. The bottom reinforcement was #4 bars at 12 inches on center in each direction. This provided restraint against stripping, handling and transportation stresses. Dowel bar dimensions were 24 inches long with a 2-inch diameter and a spacing of 15 inches on center (Figure 49).

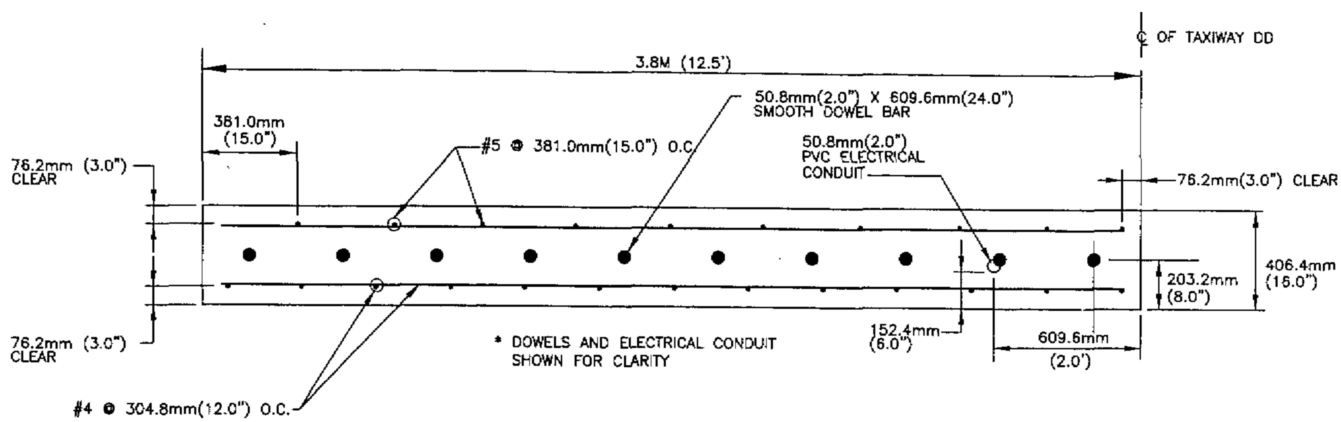


Figure 49 - La Guardia System B - PCP (Conventional) Cross-Section
(Chen, Murrell, & Larrazabal, 2004)

For both systems the Michigan Method was adopted for dowel slots (existing slab top slot dowel, PCP slab with dowel cast in). A flowable cementitious grout was used for bedding to eliminate the risk of stone dust/fine aggregate pumping. A volumetric mixer was used on site to mix the grout. The large quantity of grout provided a challenge for production. To control the slab height for final grade and bedding, a setting bolt system (eight bolts per slab) was used (Figure 50). The layouts of the slab and system sections are seen in Figure 51 and Figure 52, respectively. Taxiway lights provided unique challenge that previous airports did not have. The light cans and conduit was cast into the slab. At the end of the slab, a hand hole blockout was cast to allow the electricians to install the cable and a flexible connection.

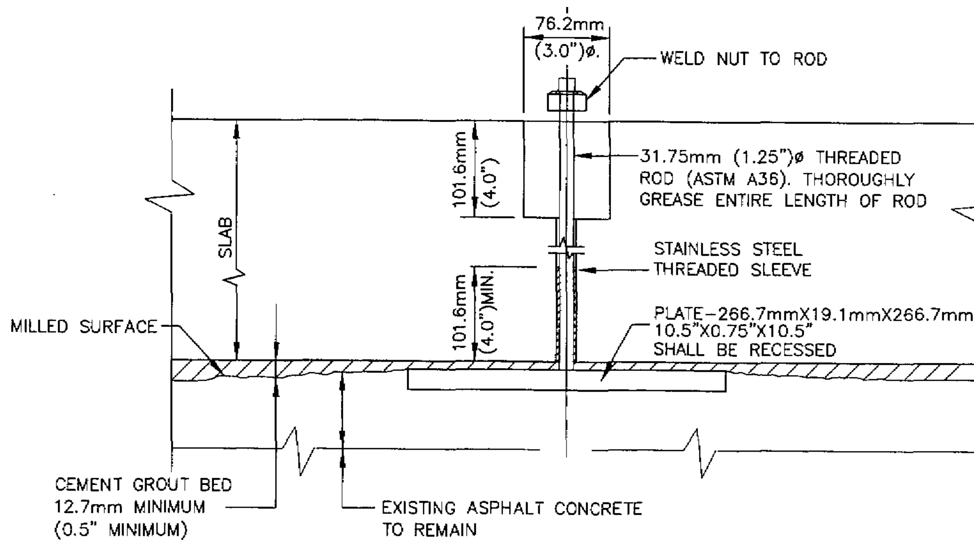


Figure 50 - La Guarding Setting Bolt Drawing
(Chen, Murrell, & Larrazabal, 2004)

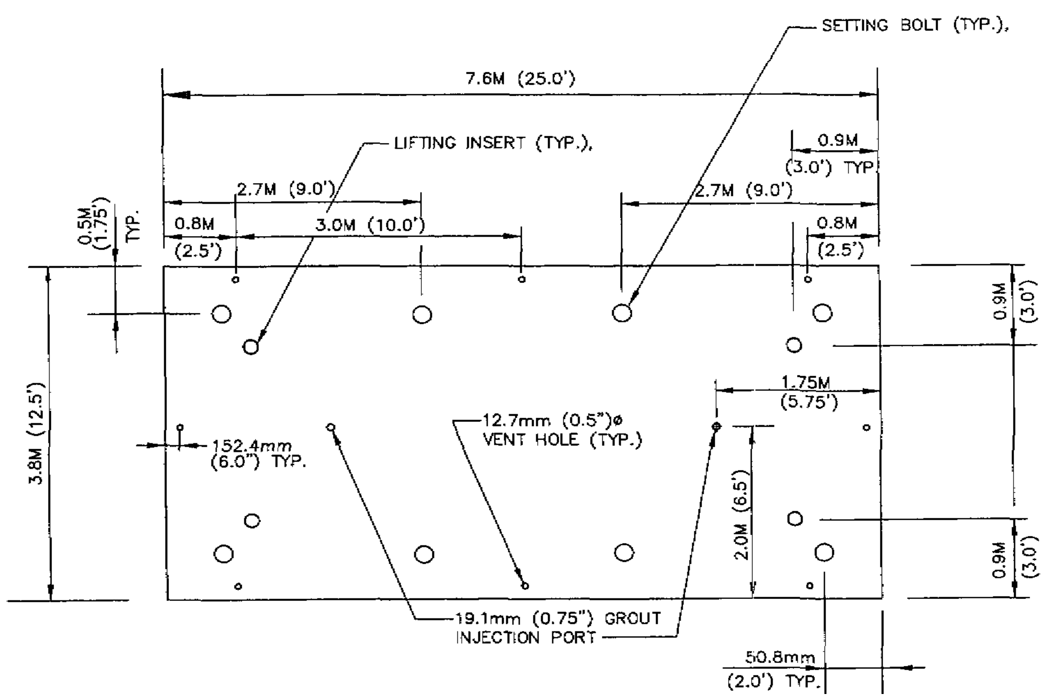
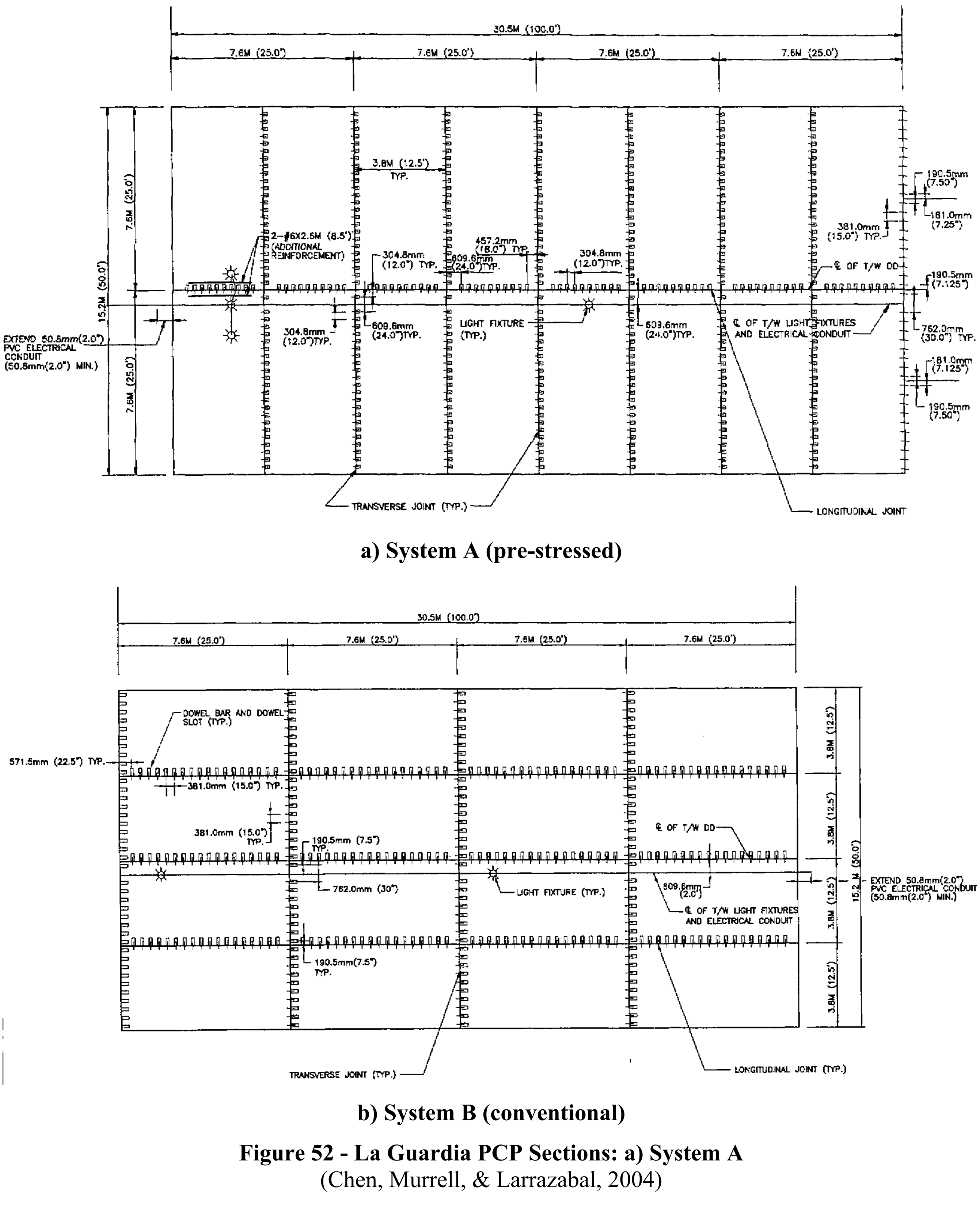


Figure 51 - La Guardia Typical PCP Plan View
(Chen, Murrell, & Larrazabal, 2004)



a) System A (pre-stressed)

b) System B (conventional)

Figure 52 - La Guardia PCP Sections: a) System A

(Chen, Murrell, & Larrazabal, 2004)

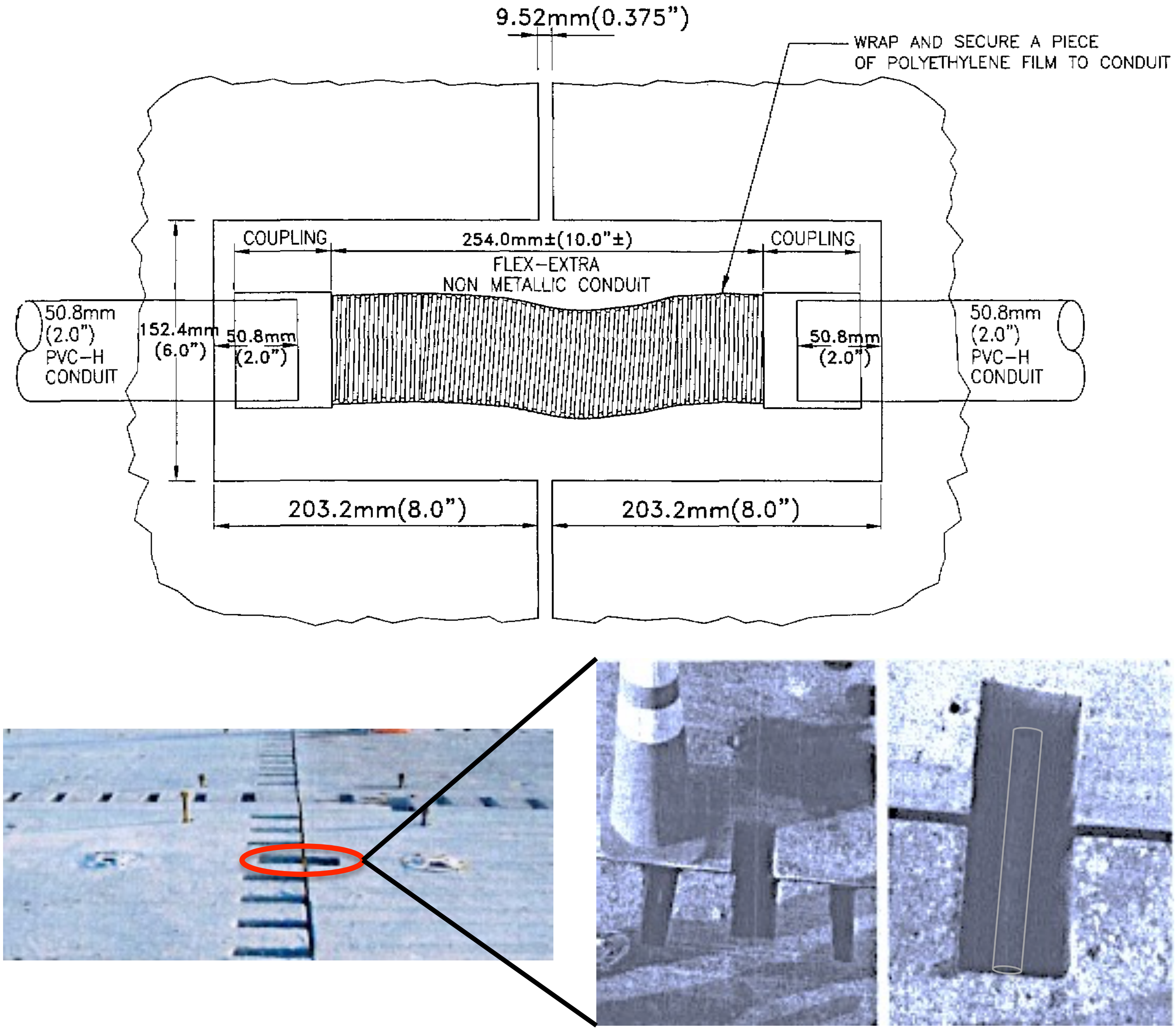
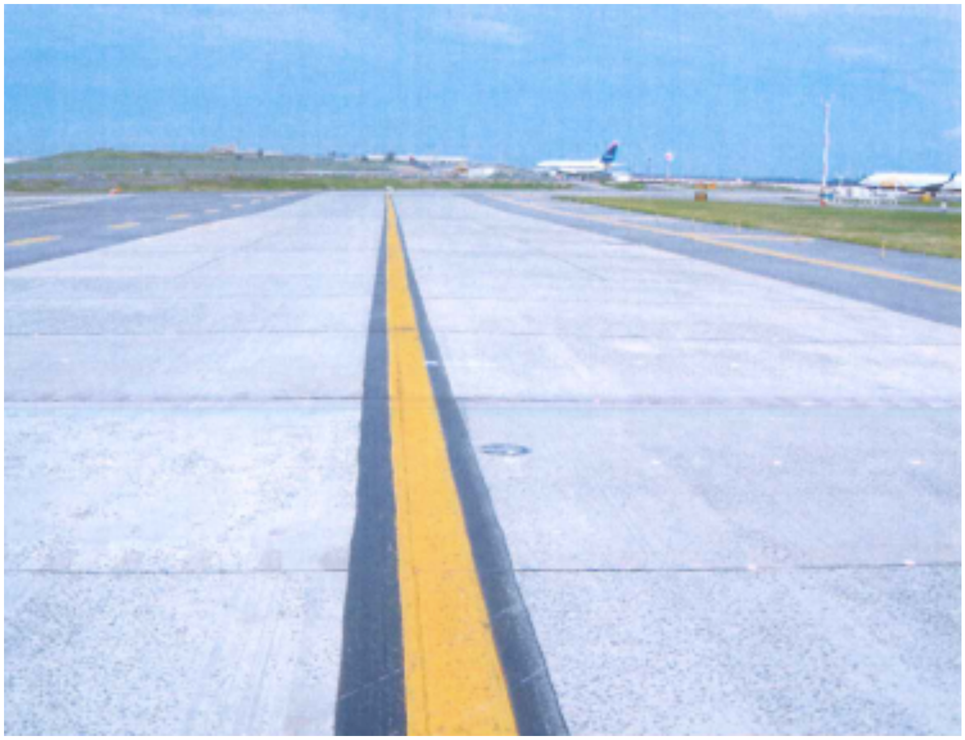


Figure 53 - La Guardia Taxiway Light Electrical Connection Detail and Construction
adapted from (Chen, Murrell, & Larrazabal, 2004)

The major construction activities are seen in Table 13. The bearing plates placement for the setting bolts took more time than planned. The contractor elected to set the plates in a motor grout with took longer than expected. During installation and panel setting, some of the sleeves in the concrete debonded and came out making adjustments impossible. Sufficient embedment will prevent this from occurring.

Table 13 - La Guardia Construction Activities

Major Activities	Install Time (hrs)
Milling Begins	0700
Bearing Plate Placement Start (for setting bolts)	1400
Panel Placement Start	1930
Day 2	
Underslab/Dowel Grouting Start	300
Joint Sealing/Clean up Start	1230
Completion/Open TW	1930
Total Time (hrs)	**36.5**



a) Post construction

b) Condition in 2010
Figure 54 - La Guardia PCP
(Chen, Murrell, & Larrazabal, 2004; Tayabji, 2010)

4.4.5 Precast Panel Use for Airports in Japan (1970 - 2014)

The Japanese Ministry of Land, Infrastructure, Transport and Tourism have used various forms of precast panel systems since 1965 with great success. The use in airports began in 1970. Japan's PCP use (total area) in airports alone, dwarfs the United States' use in highway and airports combined. Since 1970, Japan has installed 22,645,322 ft^2 (2,103,822 m^2) of PCP at airport installations (Table 27 in the Appendix). Their use has been on every airfield feature and was used for maintenance, rehabilitation and new construction lasting more than 20 years. The most common reasons for using PCP in Japan is the inability to close the facility or when large settlements are forecasted (Tsubokawa, 2015). Costs are approximately \$770/yd^2 (\$540/yd^2 with a 30% area cost factor), which is higher than CIP without the multi-day closure to aircraft. They have primarily used three methods, post-tensioning systems, traditional precast methods with varying joint connection types, and a slab lift-up method (leveling/lift rods in the slab). The lift-up method is unique and is used to raise PCP slabs after settlement. Figure 55 shows the coring, reaction bed, jack assembly, slab lift-up and grouting procedure for this method. Figure 56 shows the field performance of the jacks, which are controlled by a computer. A fourth method, 'Precast Reinforced Concrete Pavement (PRC)', has recently been developed. This is a heavily reinforced slab using a lattice truss for reinforcement (flexural strength 928 psi). The load transfer mechanism is a cotter joint. A typical cross-section is seen in Figure 57 and Figure 58 shows the lattice truss and the cotter joint. This pavement is used in locations on airports and in port facilities with very heavy loads.

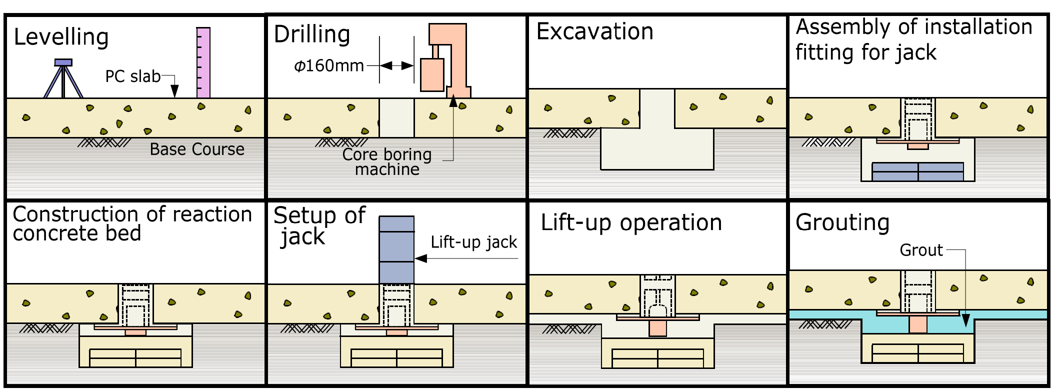


Figure 55 - Japan PCP Lift-up Method Steps
(Tsubokawa Y. , 2015)

Figure 56 - Japanese Lift-up Method Jacks in the Field
(Tsubokawa Y. , 2015)

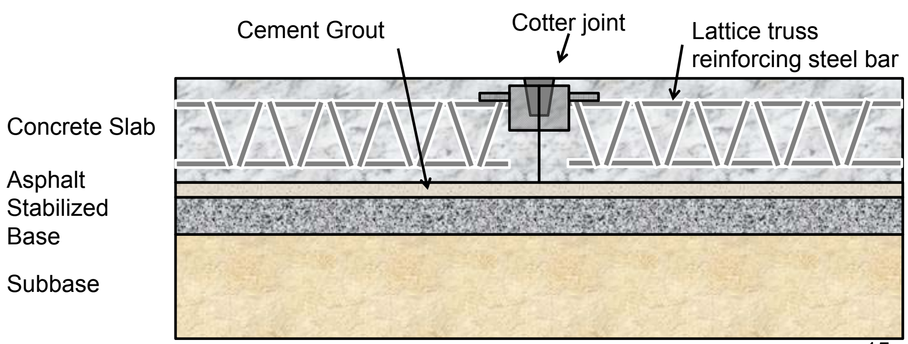


Figure 57 - Precast Reinforced Concrete Pavement Cross-Section - Japan
(Tsubokawa Y. , 2015)

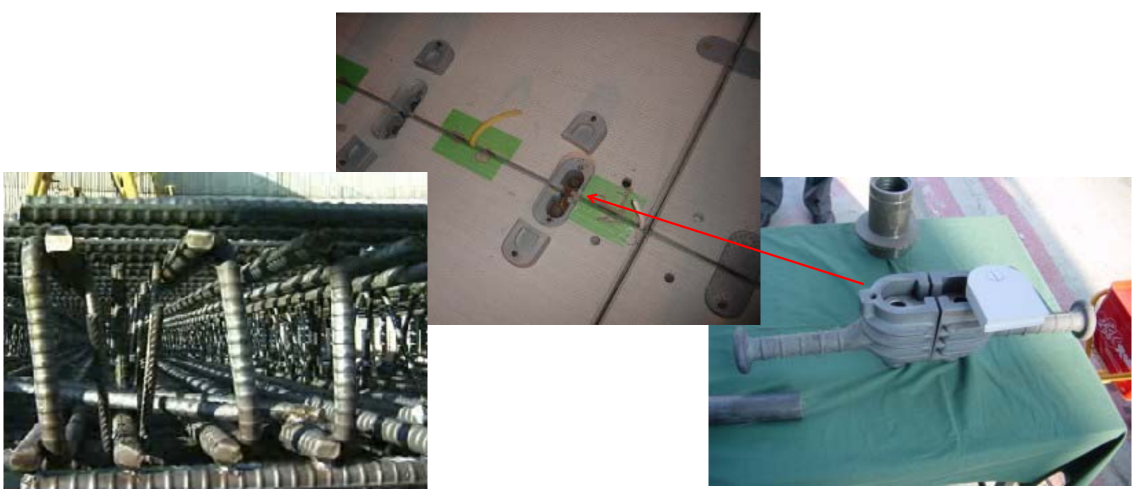


Figure 58 - Lattice Truss and Cotter Joint for Japanese Precast Reinforced Concrete Pavement
(Tsubokawa Y. , 2015)

4.5 Precast Panel Highway Installation on Illinois Route 62 – South Barrington Illinois

A site visit was conducted on 15 September 2015 in South Barrington, Illinois along a 1-mile stretch of Route 62 (Algonquin Road). The Illinois Department of Transportation used precast panel rehabilitation to repair both consecutive and intermittent locations over a 3.5-mile section on the two westbound lanes constructed in August 2000. Similar repairs were accomplished in the two eastbound lanes the previous year. The existing slabs were 12 ft by 15 ft x 12 in thick. The narrow mouth surface slot with drilled/epoxied dowel design was used for the load transfer between slabs. The project value was $1.17M and replaced 125 – 6 ft x 12ft x 12 in slabs. R.W. Dunteman was the prime contractor with J.A.C.K Coffey LLC performing the demolition work. This site visit was conducted to become familiar with the process, manpower, and equipment. Based on a visual assessment, the primary of distress was transverse cracking various degrees of joint/crack spalling were also seen (Figure 59).

Figure 59 - Typical Distress on Illinois Route 62
(Kulikowski, 2015)

The contractor was permitted to close one lane from 7:00 to 15:00 hours daily. Saw cutting could be performed up to two days prior and underslab grouting had to be performed within 48 hours of placement. This allowed to contractor the stagger crews and increase efficiency. Table 14 shows the various activity duration and manpower used for this project per slab (superscript letters correspond to letters in Figure 60). These times do not reflect the learning curve involved if the contractor is not familiar with precast work. The contractor averaged about 12 – 15 slabs per day. Figure 60 shows the construction photographs for each of the activities in Table 14. Saw cutting requires multiple passes to maintain a vertical face. If care is not taken to maintain a vertical face, the slab removal (wedged in) and installation (no contact with subgrade) will have problems and the contractor will have spend extra time to correct the deviation. The problem can be greater on deeper slabs such as those used in airports. For slab removal, a gradall machine was used instead of the lift out method. Its use was more economical based on slab size and efficiency. Some subgrade disturbance occurred but was less than typically seen for breakup and removal methods. The disturbance was re-compacted with a small compactor and an angular fine aggregate material was place over the subgrade to bring it to proper grade. Demolition and subgrade preparation accounted for 52% of construction time with the remaining going to the installation. The actual placement of the slab was less than 1% of the total construction time. The short placement time coupled with the narrow mouth surface slot allows flexibility to open to traffic expeditiously in the event of an emergency. Precast panels have been used as temporary and temporary-to-permanent (grouted one day or more later) repairs in both highways and airports (Crawford, Murphy and Tilly, Inc., 2000; Fischer, 2002; Rao, Mallela, & Littleton, 2012). Designing a tool to insert multiple dowels into drilled holes or adding more manpower would save substantial time in the overall process as it accounts for 17% of the total time.

Table 14 - Construction Activity Times and Manpower - Route 62

Construction Activity (12ft x 6ft x 12 in)**	Duration/Slab (min)	Manpower	Comments
Saw Cutting[a]	10	2	Saw operator and a flagman
Initials Demo[b] (Bobcat hydraulic hammer)	5	2	Bobcat operator and a flagman
Slab Removal[c] (Gradall)	18	4	Gradall operator, dumptruck operator, shovel man, flagman
Dowel Bar Drilling[d]	8	1	Gange drill operator
Subgrade Preparation[e]	21	4	2 shovel operators, 2 levelers/compactors
Slab Installation[f]	8	5	Crane operator, hook man, 2 place man, flagman
Insert Dowel Bars[g]	20	3	Mixer operator, 2 installers
Top Grout Dowel Bars[h]	3	3	Mixer operator, 2 installers
Underslab Grouting[i]	13	3	Mix operator, grout injector, rod man
Diamon Grinding(performed after project completion)	12	2	Grinder operator, flagman
Totals	118	29	**Work performed in multiple teams and not consecutively

a) Saw cutting **b) Initial demolition**

c) Slab removal **d) Dowel bar drilling**

e) Subgrade preparation/bedding material

Figure 60 - Route 62 PCP Installation Process

(Kulikowski, 2015)

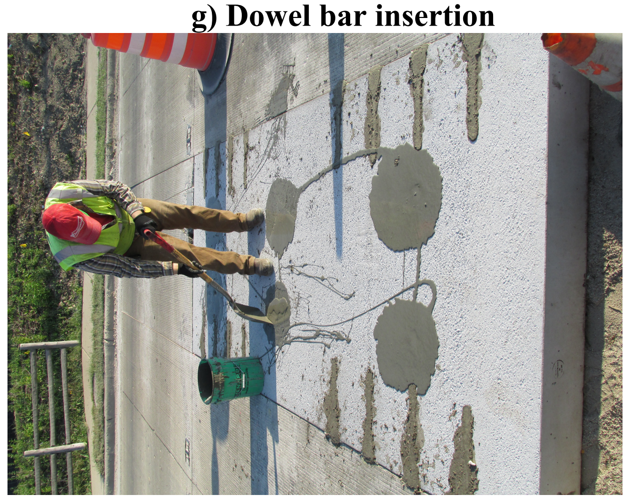
e) Subgrade preparation (grout seal)

f) PCP install

f) PCP install

g) Dowel bar insertion

h) Top grouting of dowel bars



i) Underslab grouting

Figure 60 (cont.)

4.6 Precast Panel Considerations for O'Hare

Figure 61 shows Taxiway A & B wrapping almost completely around the domestic terminal and any closures with negatively impact aircraft operations. The red line on each taxiway represents the center lane of slabs requiring rehabilitation based on initial data. The expressed constraint of night work with opening to traffic each day results in PCP as a viable rehabilitation option. As discussed, PCP rehabilitation in the United States has been used extensively in the highway industry and to a lesser degree in airports. By replacing distressed panels, the overall condition of the taxiways will improve, the service life of the taxiway will be extended, and the airline operation impact will be minimized.

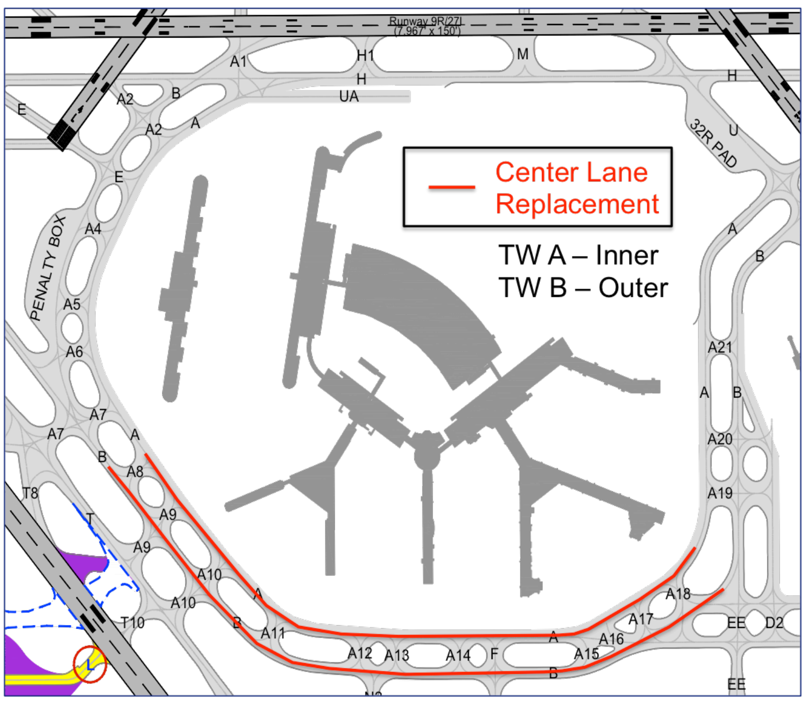


Figure 61 - ORD Taxiways A & B Layout with Center Lane Slabs Market for Rehabilitation

To streamline the design and construction process, an integrated project team, which including a knowledgeable precast panel installation contractor. Although contracting regulations may prohibit pre-selection of a construction contractor, the use of informational design sessions and request for information from contractors can provide similar benefits. Based on the size of rehabilitation required, many contractors will be interested and can provide a competitive bidding arena. Due to the existing 25-foot panel size and weight (83 tons), replacement panels may need to be reduced to approximately 12.5 x 25 foot (42.5 tons). The reduction in slab size allows more common size cranes, dump trucks and flat bed trucks to be employed. The panel dimensions should be 0.5 inch smaller on each side to allow for placement. The panel can maintain the existing 22-inch depth. A depth reduction of one-quarter to one-half an inch is acceptable to account for variations in the existing pavement and prepared subgrade. Often diamond grinding is performed to eliminate elevation differences between adjacent slabs and provide more continuous texture to the slab surfaces.

Another design consideration is the bituminous aggregate mixture (BAM) underneath the PCC layer. Based on core samples from 2013 and 2015, the BAM layer exhibits good bonding to the concrete and sections of this will be ripped up during construction. This will cause an irregular surface that will need to be repaired prior to PCP placement. The repair using similar asphalt concrete is not recommended. This option will require additional equipment to be placed into the hole for tack coat application and compaction, which will increase construction time. A more rapid approach is to use a self-leveling, lean concrete mix with high early strength. This may also be used as a grout with a fine-aggregate bedding. This concrete will fill the voids left during removal while providing uniform slab support and strength.

This panel size allows the panels to be manufactured in a controlled, plant environment and transported to the airfield via public roads if necessary. Manufacturing the panels at a location on the airfield is preferable since this can reduce transportation costs. It is important to provide controlled condition for the curing. Increasing the production quantity on-site will provide opportunities to streamline processes. For example, instead of using traditional all-terrain or crawler cranes, which require placing/replacing outriggers, a straddle crane maybe used in the production and then transport the PCP slabs over to the installation location. For manufacturing sites, these straddle cranes are custom built and require manufacturer assembly, which has higher costs compared to a typical 175 – 250 ton rental crane.

To ensure the contractor is ready for full-time night operations a test panel removal/placement should be completed in a location that can allow for continuous closure until the process is approved and allows the contractor to work out logistical issues and give the confidence in production. It is more economical and time efficient to the project to have this test panel than to have an extended taxiway closure under penalty clauses. A thorough walk-through should occur for the backup plan(s) in the event an unintended issue occurs. For example, a plan may include having eight to twelve, 12.5-foot panels on hand that can be placed in the hole and opened for traffic until the next night of construction. From assessments, not all panels may be able to be removed via crane because of extensive cracking. The wire mesh will assist in holding the pieces together, but when it is not the case, the contractor should have additional equipment scheduled for the removal of these panels. A significant challenge that should be addressed with an integrated project team is the electrical connections of the lights. There is no issue pre-casting electrical conduit and the light base can in the concrete slab. The challenge is during the installation, the electrician needs enough room to splice/install flexible conduit from one slab to the next. After the project is completed new wire may be ran through the entire section for continuity.

Slab replacement order should also be considered. Based on current HWD and panel distresses, the keel section is in the poorest condition. There are panels north and south of center that exhibit distresses but have adequate load transfer and therefore do not need to be replaced at this time. Figure 62 shows two methods parallel and perpendicular to TW replacement. Replacement of the keel section (parallel to TW) provides efficiencies in construction time and future rehabilitation. First, the center slab has taxiway centerline lights that must be replaced. The light can base and conduit can be cast into the slab with a hand hole on each end for the electrical wire splicing. Parallel placement will allow more rapid splicing. Second, tie bar receptacles can be cast into the longitudinal slab face for future 'screw-in' headed tie bars for rehabilitation of slabs adjacent to the center lane. This is beneficial were there is the possibility of slab drift or aircraft using latter taxiways between TW A & B. Lastly, continuous parallel replacement allows load transfer to be established from slab to slab more consistently with continuous replacement.

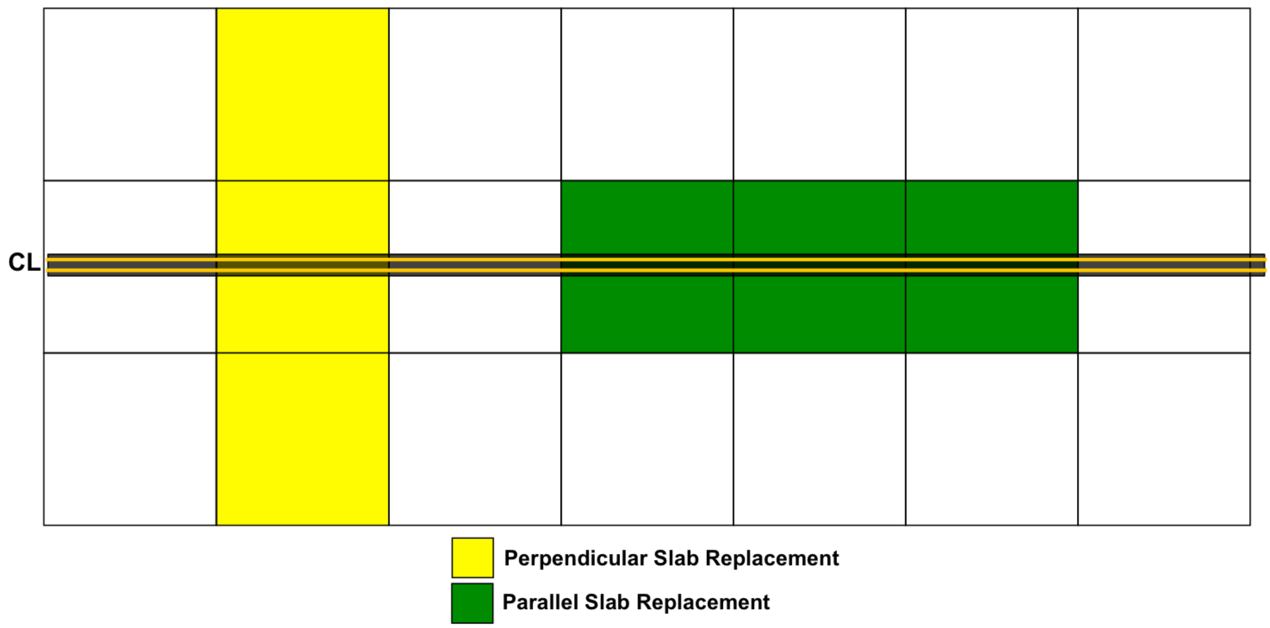


Figure 62 - PCP Slab Replacement Order Options

PCP rehabilitation is a proven, long-term rehabilitation strategy at multiple large national airports and international airports. If the base layers and subsurface drainage is not compromised, this method is substantially faster and uses less material than reconstruction. PCP provides high quality concrete product that is placed in an expeditious manner overnight with minimal impact to regular aircraft operations.

CHAPTER 5 – LIFE CYCLE ASSESSMENT OF TAXIWAY A&B USING LCA-AIR TOOL

After evaluating a wide suite of rehabilitation strategies for ORD's Taxiways A&B, three strategies were selected as cases for further investigation: precast concrete panel replacement, rubblization with mill/AC inlay and full-depth reconstruction. These rehabilitations occur at the 30-year point and will extend the taxiway's life to 50 years. The rubblization with mill/AC inlay has a potential to last 10 to 15 years, depending on the traffic level and thickness of the AC inlay, after which a milling of the old asphalt/new inlay will occur. For the assessment, this milling of the inlay occurs at year 40 to ensure the pavement reaches 50 years. The PCP or full-depth reconstruction will last between 20 to 40 years. For this assessment a 20-year extension was used. Current data on the remaining slabs that may not be rehabilitated especially in low traffic path zones are they still have good remaining life and are performing well. An extensive cost analysis was not part of this study. This chapter focuses on the LCA for each case in the rehabilitation for 200, keel section slabs (125,000 ft^2) on the southern side of each TW. Each strategy rehabilitates the same area per TW (reference Figure 61) but the depth and materials are dependent on the method. Figure 63 shows the cross-sections for original construction and each rehabilitation strategy. The red dashed line indicates the depth of each strategy.

The inputs for each phase are discussed. The results for multiple TRACI indicators are presented with a focus on energy and GWP with respect to square yard and pound-mile. The MP for initial construction and U phases are assumed to be the same for each case. Therefore, the case study will focus on the impact results from the CMR phase that includes the impact from all machinery used in initial construction, the maintenance and rehabilitation in addition to the new materials used in the repairs and rehabilitation.

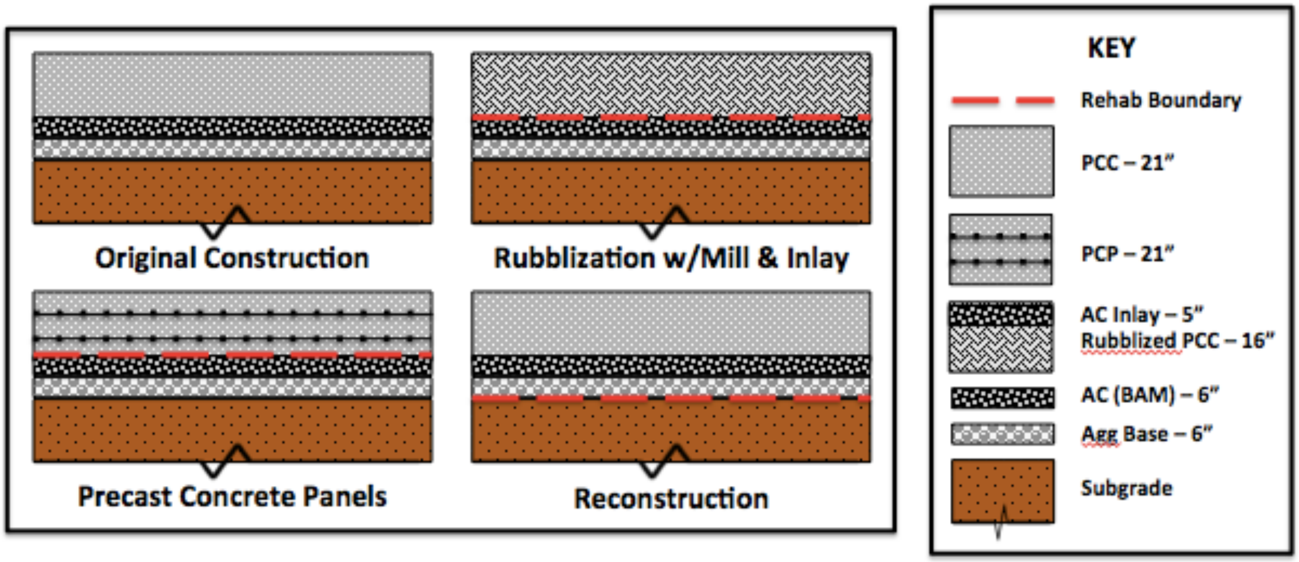


Figure 63 - Rehabilitation Strategy Cross-Sections

5.1 Geometry, Pavement Structure and Mix Design Inputs for Initials Construction

The geometry and pavement structure used for initial construction was based on the as-built drawings as seen in Table 4 with the width and length of each TW being 75 feet (Figure 11) and 11,088 feet. The concrete, asphalt and aggregate base densities were assumed to be 150, 145 and 140 pounds/ft^3, respectively. These slabs had doweled transverse joints and for the most part include welded wire mesh 6.5 inches from the surface. Individual slab weight is 165,000 pounds with 942 pounds from steel contribution (0.0571%). The original mix designs were not available, so the following mix designs in Table 15 were used for the analysis in the construction and maintenance materials. A prime coat was used on the crushed aggregate base and a tack coat was used between asphalt layers. It was assumed the 6 – 7 inch asphalt layers were placed in two lifts. The distance from the concrete and asphalt plant to the construction site was five miles.

Table 15 - Mix Designs for LCA Case Studies

AC	% Weight of Surface Mix	% Weight of Base Mix
Virgin coarse crushed aggregate	71.325	74.178
Virgin fine crushed aggregate	20.922	20.922
Virgin natural sand	0.000	0.000
Coarse RAP (3.6% binder)	0.000	0.000
Fine RAP (6.4% binder)	0.000	0.000
Mineral Filler	2.853	0.571
Total binder	4.900	5.000
Distance from plant to site (miles)	5	5
PCC	**JPCP (lbs/yd^3)**	
Virgin coarse crushed aggregate	2,075	
Virgin fine crushed aggregate	1,056	
Portland cement	401	
Fly Ash	134	
Water	240	
Slag cement	0	
Distance from Plant to Site	5	

5.2 Construction, Maintenance and Rehabilitation Equipment and Schedules

As discussed previously, the impacts for the CMR phase is a function of the equipment used, their productivity/fuel efficiency and the impacts associated with the repair materials. The productivity and fuel consumption is impacted by the operator's competency level, the material type and cycle times performing each activity. Based on experience, industry averages, interviews and literature the productivity and fuel consumption were calculated (Muench, et al., 2011; Ross, 2011; Pullen, Edwards, Rutland, & Tingle, 2014; CATERPILLAR, 2015; Craftco, 2015; Bockes, 2015; Shinners, 2015; Shinners, 2015; Wirtgen Group, 2015). When fuel consumption was not available, EPA NONROADS database was used based on the engine horsepower (Environmental Protection Agency, 2008). Table 28 in the Appendix shows the values used for productivity and fuel consumption in this study.

The initial construction impacts of the TWs are the same for each case. The AC portions consisted of: the AC base under the PCC surface and the AC shoulders on each side of the TWs. The PCC portion was only for the three, paving lane slabs on each TW. Equipment was selected for each task and then based on the geometry (volume and tonnage) and productivity/fuel efficiency the diesel combustion for each activity was calculated. The activities, equipment and fuel consumption values are in Table 29 and Table 30 in the Appendix. The total fuel consumed during construction for the AC base (1,663,200 ft^2)

and AC shoulders (1,108,800 ft^2) 11,899 gallons. The total fuel consumed during construction for the PCC 15,794 gallons. (A basis of square feet should not be used to compare the asphalt work vs. concrete work, as the volume is significantly different.)

Maintenance and repair at airports occurs around the clock and very few activities are consistently scheduled to reoccur. A recurring maintenance/rehabilitation schedule was not available so schedules and quantities were established. For this study, the maintenance activities were aggregated and assumed to occur at specific years. Below is a list of the general activity intervals used for each case. The AC activities are on the shoulders with the exception of the reconstruction (base layer) and the rubbilization with mill/inlay. The occurrences and quantities used are in Table 31 to Table 36 in the Appendix.

PCC

- Restriping airfield markings – every ten years
- Joint and crack sealing – every eight years
- Full and partial depth repairs – every fifteen years
- Brooming – every other day

AC & AC Shoulders

- Restriping airfield markings – every ten years
- Crack sealing – every ten years
- Asphalt patching – every fifteen years
- Mill/inlay – every fifteen years
- Mill/inlay – 10 years after the initial rubblization with mill/inlay section

5.3 Use Phase Components

As discussed in Chapter 2, the use (U) phase dominates the other phases because of the fuel consumed when including half of the time in flight. However, the U phase has a small contribution when only the additional fuel consumed because of a change in roughness is calculated. For each of the three cases the change in roughness of the pavement surface was assumed to be similar.

The aircraft selected for use and their associated weights/operations are in Table 16. Based on the ICAO the actual weight of 75% of the MTOW was used. MTOWs were based on manufacture specifications. Four aircraft were selected to represent the eight aircraft categories (MTOW) trafficking

TW A and B. The B737 represents groups one through four, the A330 represents groups five and six, the B777 represents group seven and the B747 represents group eight. The number of operations was based on the 2018-projected traffic. Due to the small quantity of operations in groups five through 8 the average operations was divided by three and attributed to each aircraft.

Table 16 - Use Phase Aircraft Information

Aircraft Type	Operation weight (75% MTOW) (lbs)	Yearly Number of Operations	Air flight Duration (hrs)	Max Weight (lbs)
B747-200B	624,750	1738	2	833,000
B777-200 ER	570,000	1738	2	760,000
A330-300 opt	390,525	1738	2	520,700
B737-700	115,875	62500	2	154,500

The other factors considered in the U phase were lighting and snow removal. There were 440 centerline lights and 887 edge lights used in the calculation of the electricity impact. The lights are used for night operations and also during daytime inclement weather. Therefore an average time of 12 hours per day was assumed for each case. Twenty snow occurrences were assumed for each case.

5.4 Life Cycle Assessment for Rubblization with Mill/AC Inlay

This strategy consists of rubblizing the existing PCC pavement and providing an AC inlay. Due to the TWs connection to other features, changes in elevation can be detrimental to operations or require significant investment to remedy. The method for this rehabilitation consists of using a two-step breaking process. First, a guillotine style breaker will be dropped breaking the slab in the larger pieces (similar to the break and seat methods of highways). Immediately following this, a multi-head breaker will reduce the sizes varying from a few inches down to 12-15 inches at the bottom of the slab. Finally, milling machine removes the specified amount of rubblized PCC.

This two-phase breaking process has been used for about 20 years on both highways and pavement structures. Grand Forks AFB in North Dakota rubblized their runway in preparation for an asphalt overlay in 2005. Multiple machines were used to maximize productivity in a short construction period, which is important for night work at ORD (Antigo Construction, 2015). The pavement thickness' at Grand Forks AFB (16 – 29 inches) was comparable to ORD's 21 inches. A resonance breaker was initially used but had issues with low productivity, inability to rubbilize through the pavement depth, and required constant specialized maintenance. Subsequently, the two-phase breaking process was implemented to increase productivity (Rudolf, 2015). Additionally, elevation restrictions require maintaining existing profiles and thus milling the rubblized PCC must be considered. This technique was first conducted in 2013 at Grifiss International Airport on TWs A, C, D and K, in Rome, NY, which included a five-inch AC overlay. The original PCC thickness was 16 – 24 inches. The rubblization prior to milling accelerated the cold milling process, decreased machine wear and was deemed successful for the contractors and the airport (Shinners, 2015). Figure 64 shows the milling process.

Figure 64 - Milling of Rubblized PCC Runway at Griffiss International Airport
(Antigo Construction, 2013)

More recently a rubblization with a mill/inlay with an AC overlay was conducted in July/August 2015 at Coles County Airport in Charleston, IL. The rubblized PCC was 14 inches over a 7-inch bituminous base layer. The constructed AC overlay was a minimum of four inches thick, with an average of five and a half as found by ground penetrating radar. The project called for milling in various locations to meet elevations of connecting taxiways. To accelerate the process and eliminate reflective cracking the project was modified and rubblization/milling was allowed. Figure 65 shows the guillotine breaker (dropped every 8-12 inches), the mutli-head breaker and z-grid roller. The final product after each step is also seen. The test pit shows the effectiveness of the two-step breaking process. Figure 66 shows the milling and the subsequent overlay using a stringless paver. No issues were reported by the contractor and airport owner with this design and construction process.

Figure 65 - Rubblization at Coles County Airport - Charleston, IL
(Kulikowski, 2015)

Figure 66 - Milling and Asphalt Paving at Coles County Airport - Charleston, IL
(Hanson Engineering, 2015)

The standard maintenance used was discussed in Chapter 5.3. At 30 years a large rehabilitation is performed on the TWs A&B. The following LCA analyzes the rubblization of 250,000 ft^2 (200 slabs per TW) and five inches of milling with a five-inch AC inlay. For ORD, milling deeper than five inches is not feasible because of the wire mesh at approximately six inches from the surface.

Appropriate equipment was selected for the CMR activities as seen in Table 37 and Table 38 (Appendix) for PCC and AC, respectively. Figure 67 shows the fuel consumed for each activity. For many activities it is a summation of the fuel consumption from multiple pieces of equipment. For example, the land clearing activity uses the fuel consumed from a dozer, loader and dump truck. The highest fuel consumption activities were brooming (112,721 gal), crack sealing (31,771 gal), restriping (16,746 gal) and land clearing (12,328 gal).

Converting the brooming machine to an electric source will eliminate the fuel consumed for brooming operations. There will be an adjusted impact for electrical consumption with use. Adjusting the brooming schedule will also save fuel. Reducing the cleaning to once every five days will provide a 10% reduction in total fuel consumed. This must be balanced with increase risk of increase FOD on the TWs. Crack sealing is a time and energy intensive activity. The tank must remain at a high temperature to ensure the sealant is still flowable. The sealant is placed by and individual with a wand walking every crack. The use of alternative, lower temperature sealant will reduce some of the cost.

Using asset optimization principles contracts can be structured to only include cracks of a certain size, which will reduce the impact as well. Similar asset management principles can be used to reduce the frequency or quantity of markings restriped. For land clearing, it was assumed the clearing for the entire depth of the pavement structure, in this case 33 inches. Stabilizing the subgrade may result in additional saving because of a reduction of aggregate subbase and total pavement thickness. The main rehabilitation activity of rubblization consumed 954 gallons of fuel and the additional AC inlays (apart from the shoulder inlays) consumed 553 gallons to place. The total fuel combusted was one component used to determine the environmental impacts for the CMR phase. Figure 68 shows the percent contribution of fuel for each activity (values are read down the legend and clockwise on the graph). The total fuel consumed for the CMR phase was 204,568 gallons.

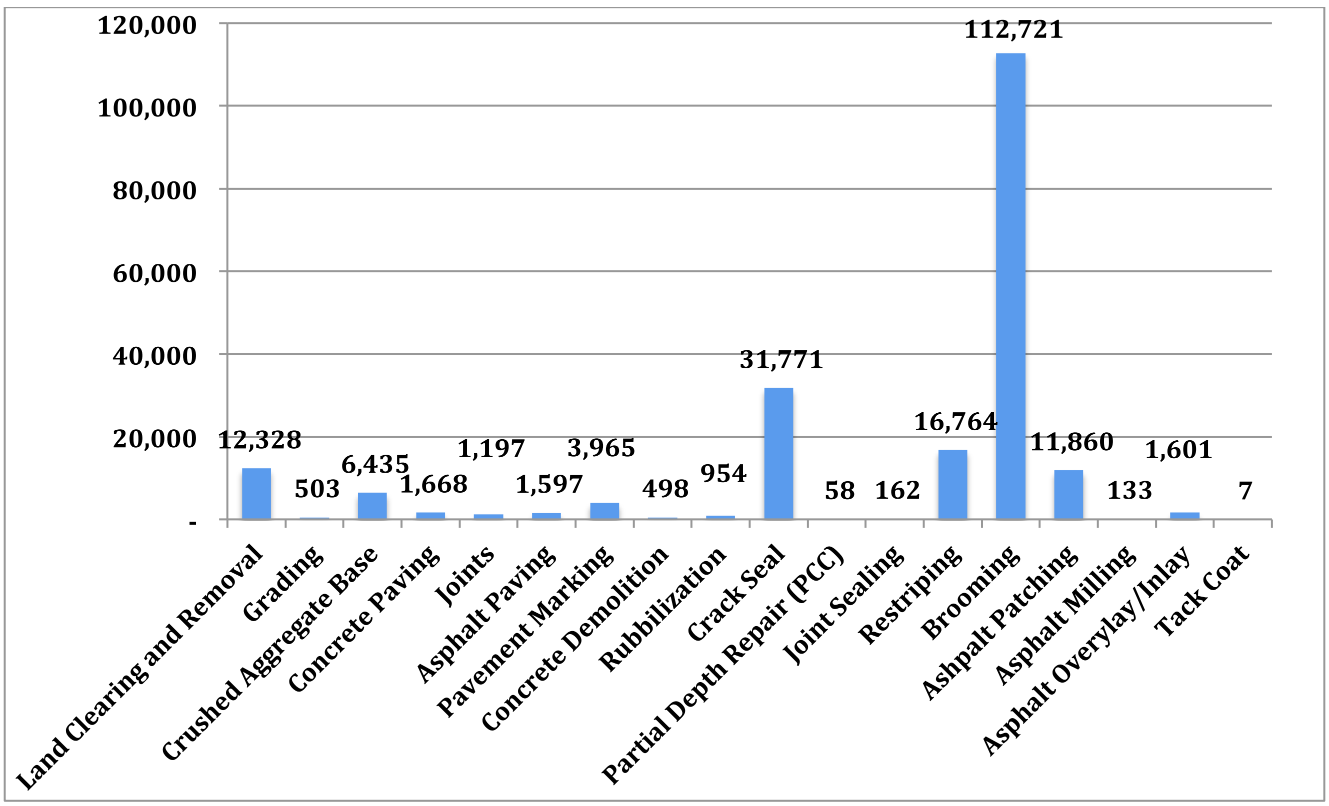


Figure 67 – CMR Fuel Consumption per Activity – Rubblization with Mill/AC Inlay

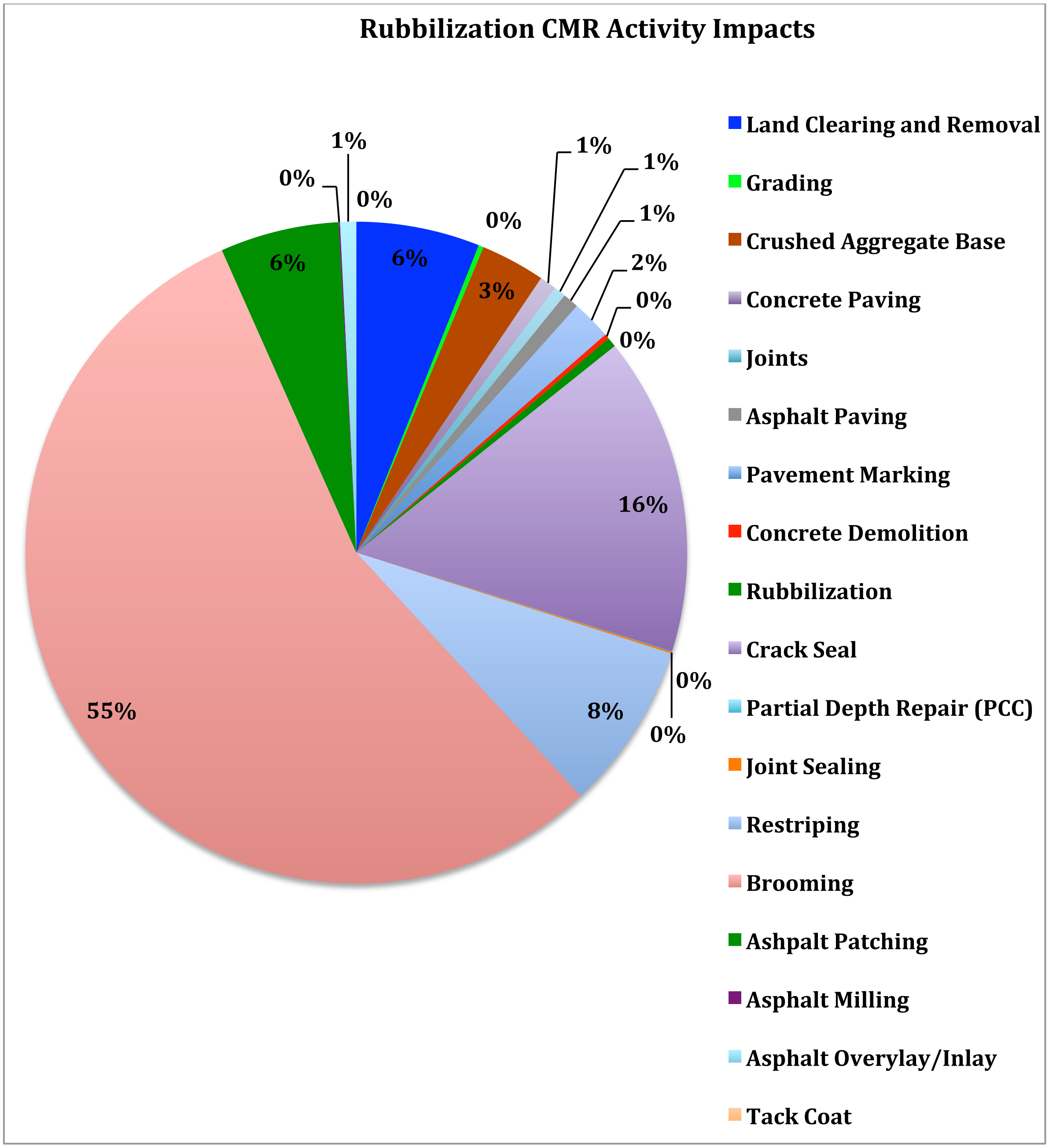


Figure 68 – CMR Fuel Consumption Impact Contribution – Rubblization with Mill/AC Inlay

The second component used to determine the total CMR impacts was the materials used in the maintenance and the rehabilitation. As expected, the rubbilization with mill/inlay used the least amount of material because the 16 of the 21 inches of PCC remain in place. The only new material added for the rehabilitation is the prime/tack coats and the new five inches of inlayed asphalt. Table 13 shows the material impacts for the maintenance and the rehabilitation. Rubblization showed a 9% and 24%

reduction in energy compared to precast panels and reconstruction respectively. For GWP it was 1% higher than precast panels and 1% lower than reconstruction.

Table 17 - Material Impacts for CMR Phase – Rubblization with Mill/AC Inlay

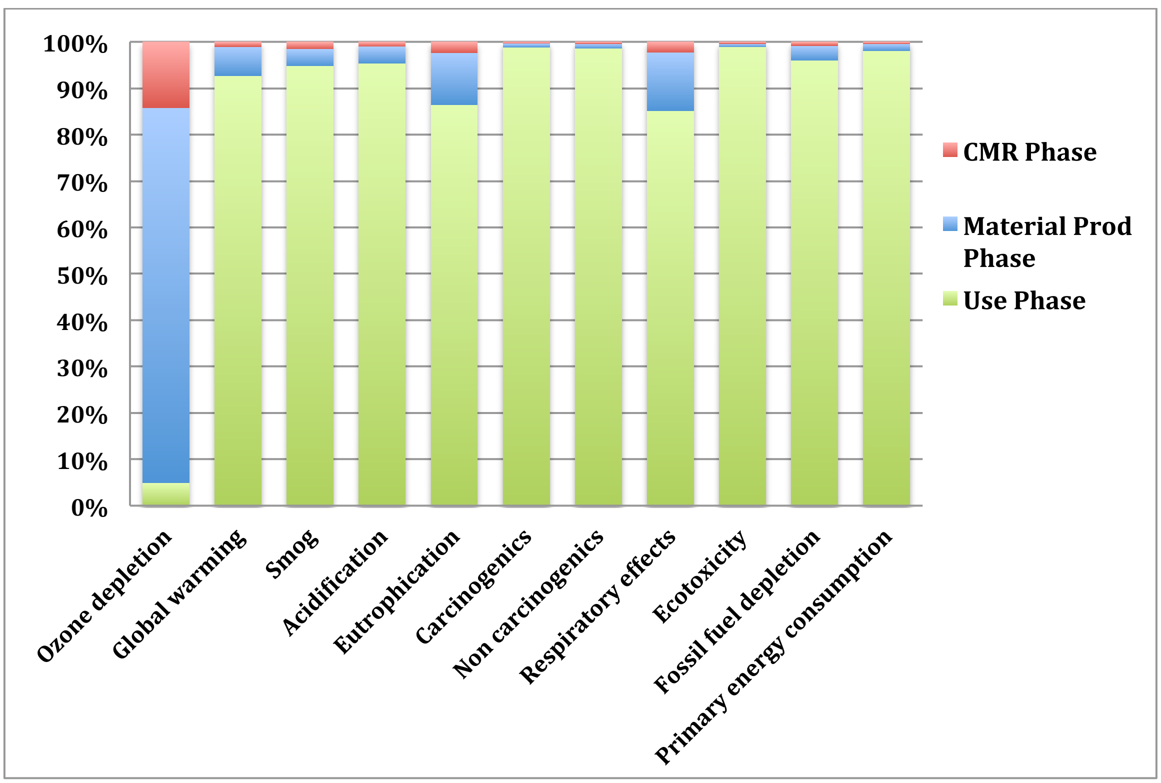
Impact category	Unit	Rubblization CMR Mat Impacts
Ozone depletion	**kg CFC-11 eq**	3.13E+00
Global warming potential	**kg CO2 eq**	4.95E+06
Smog	**kg O3 eq**	3.43E+05
Acidification	**kg SO2 eq**	4.66E+04
Eutrophication	**kg N eq**	9.41E+03
Carcinogenics	**CTUh**	1.67E-01
Non carcinogenics	**CTUh**	1.72E+00
Respiratory effects	**kg PM2.5 eq**	4.22E+03
Ecotoxicity	**CTUe**	3.24E+07
Fossil fuel depletion	**MJ surplus**	5.85E+07
Primary energy consumption (renewable + non-renewable)	**MJ**	2.06E+08

5.4.1 Rubbilization with Mill/AC Inlay Impacts per Phase and Functional Units

The total impact from each phase was summed and then divided by the functional units for the airport. Table 18 shows the total values for the impacts using both aircraft fuel consumed for one-half the time in flight as well as for only the aircraft fuel consumed because of an increase in IRI. Figure 69a and 68b show the percent contribution from each phase. As discussed previously, the fuel consumed by the aircraft over 40 years dominates the LCA. Although not in contact with the pavement there is still an environmental impact that doesn't disappear when the plane leaves the airport. When only using the fuel consumed by change in IRI, MP phase accounts for about 62%, CMR phase accounts for 15% and the use phase is approximately 23%. This demonstrates a significant difference between highway and airfield pavement LCAs as noted in Chapter 2.

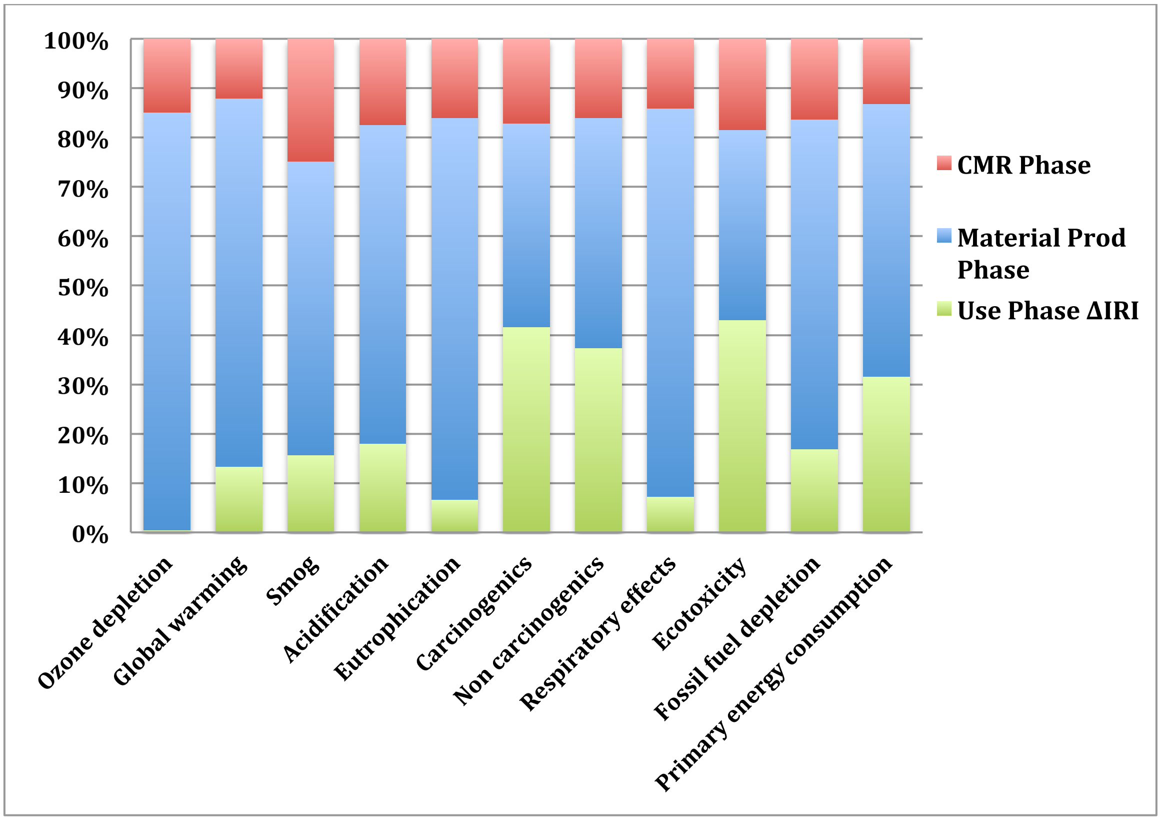
Table 18 - Total Impacts per Functional Units – Rubblization with Mill/Inlay Case

Rubblization and Inlay Panel Case		TW A&B		TW A&B	
Impact category	Unit	Total Impact Per yd^2	Total Impact Per lb-mile	Total Impact Per yd^2 (ΔIRI Only)	Total Impact Per lb-mile (ΔIRI Only)
Ozone depletion	kg CFC-11 eq	7.181E-05	4.988E-19	1.144E-04	1.347E-17
Global warming	kg CO2 eq	2.395E+03	4.310E-10	2.004E+02	3.934E-11
Smog	kg O3 eq	3.014E+02	5.583E-11	1.849E+01	3.628E-12
Acidification	kg SO2 eq	2.662E+01	4.948E-12	1.501E+00	2.946E-13
Eutrophication	kg N eq	1.608E+00	2.703E-13	2.341E-01	4.595E-14
Carcinogenics	CTUh	1.950E-04	3.782E-17	3.879E-06	7.613E-19
Non-carcinogenics	CTUh	1.878E-03	3.632E-16	4.194E-05	8.231E-18
Respiratory effects	kg PM2.5 eq	7.071E-01	1.162E-13	1.135E-01	2.228E-14
Ecotoxicity	CTUe	3.620E+04	7.025E-09	6.915E+02	1.357E-10
Fossil fuel depletion	MJ surplus	2.641E+04	4.973E-09	1.265E+03	2.483E-10
Primary energy consumption (renewable + non-renewable)	TJ	0.18612	3.575E-08	0.00518	1.017E-09



a) percent contribution including time-in-flight fuel consumption

Figure 69 - Phase Impact Contributions – Rubblization and Mill/Inlay Case



b) percent contribution including only aircraft fuel consumed from change in IRI

Figure 69 (cont.)

5.5 Life Cycle Assessment for Precast Concrete Panels

An in depth discussion on the precast panel method from precast panel is found in Chapter 5. Figure 63 shows the depth of repair (21 inches of PCC). The slab lift out method assumed for removal. Appropriate equipment was selected for the CMR activities as seen in Table 39 and Table 40 (Appendix) for PCC and AC. Figure 70 shows the fuel consumed for each activity. The highest fuel consumption activities were brooming (112,721 gal), crack sealing (31,072 gal), restriping (16,222 gal) and land clearing (12,328 gal).

Brooming impacts are similar to the rubbilization case study. Crack sealing is slightly less than the rubblization case because the PCP repair section will not require the same crack sealing as the AC inlay. The main rehabilitation activities were concrete pavement demolition, PCP placement, and diamond grinding. The concrete demolition consumed an additional 523 gallons of fuel. The PCP placement consumed 2,937 gallons and diamond grinding added 761 gallons of fuel. It was assumed the entire repair area was diamond ground. Close coordination with the fabricator and installer can ensure tight tolerances are achieved and only spot grinding is necessary. The amount of patching is reduced on the rehabilitated section compared to rubblization because of the increased durability of concrete. The total fuel combusted was one component used to determine the environmental impacts for the CMR phase. Figure 71 shows the percent contribution of fuel for each activity (values are read down the legend and clockwise on the graph). The total fuel consumed for the CMR phase was 206,078 gallons, which is 2,052 gallons more than rubblization. The rubblization method is an efficient operation for demolition (leaves material in place) and paving is also fast providing for key reductions.

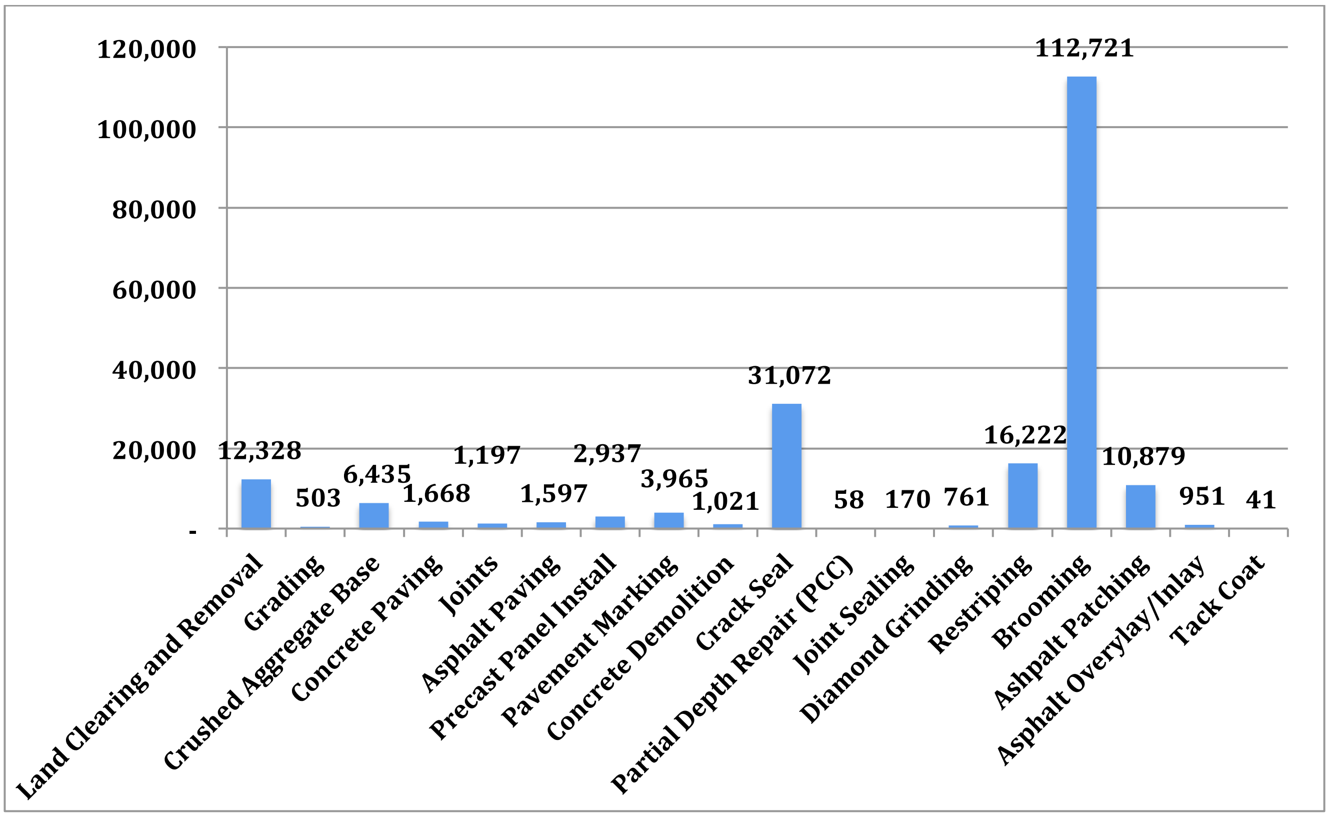


Figure 70 – CMR Fuel Consumption per Activity - Precast

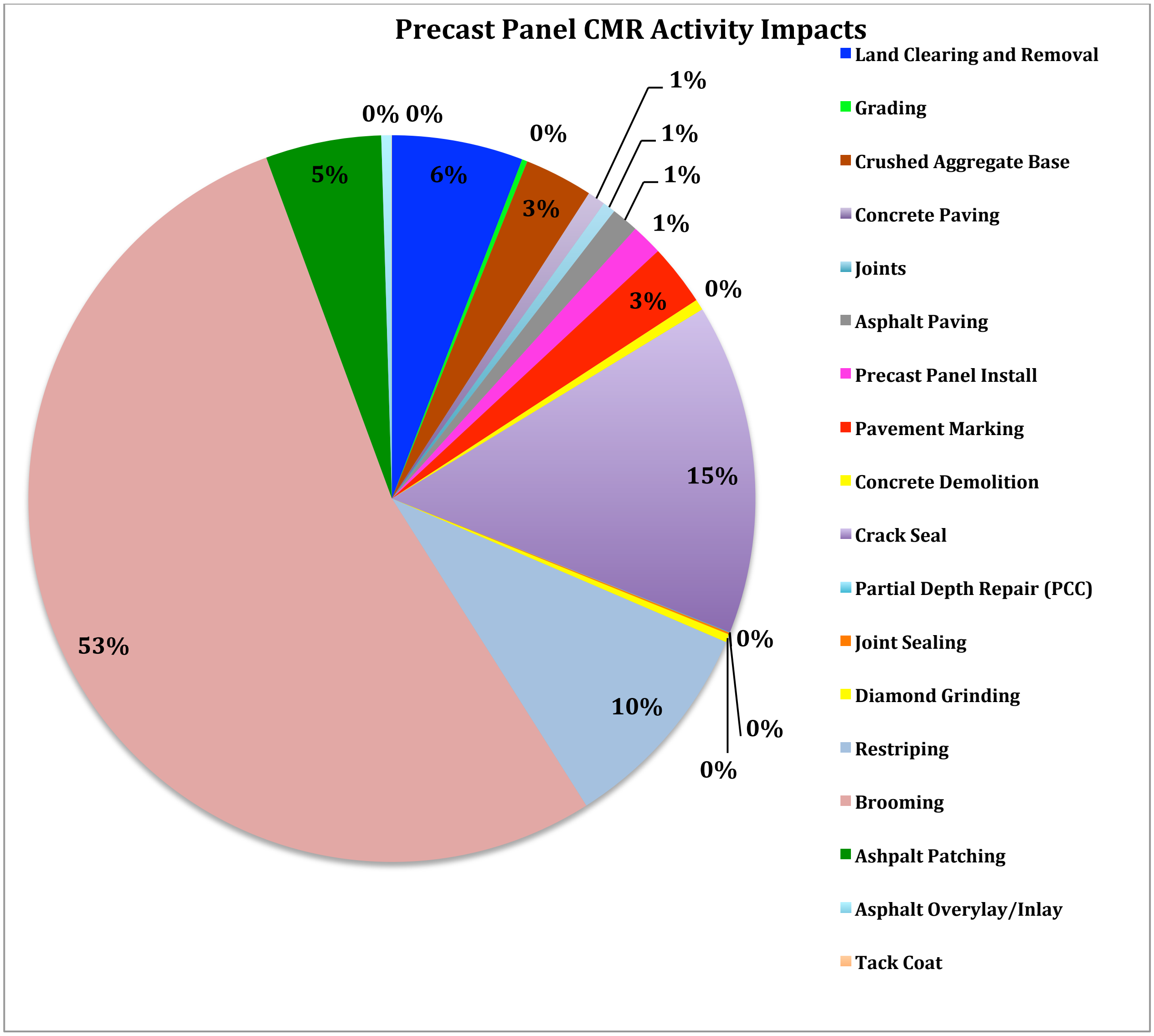


Figure 71 – CMR Fuel Consumption Impact Contribution - Precast

The second component used to determine the total CMR impacts was the materials used in the maintenance and the rehabilitation process. The precast strategy replaced the second most amount of material following reconstruction and subsequently will have higher impacts than rubblization as well as a longer service life. The new material includes some base leveling fine aggregate and new reinforcement in the PCC slabs. Table 19 shows the material impacts for the maintenance and the rehabilitation. A 9% increase in energy and a 1% decrease in GWP are seen in the PCP method compared to rubblization. These values are 2% and 15% lower than the full reconstruction method.

Table 19 - Material Impacts for CMR Phase – Precast Panels

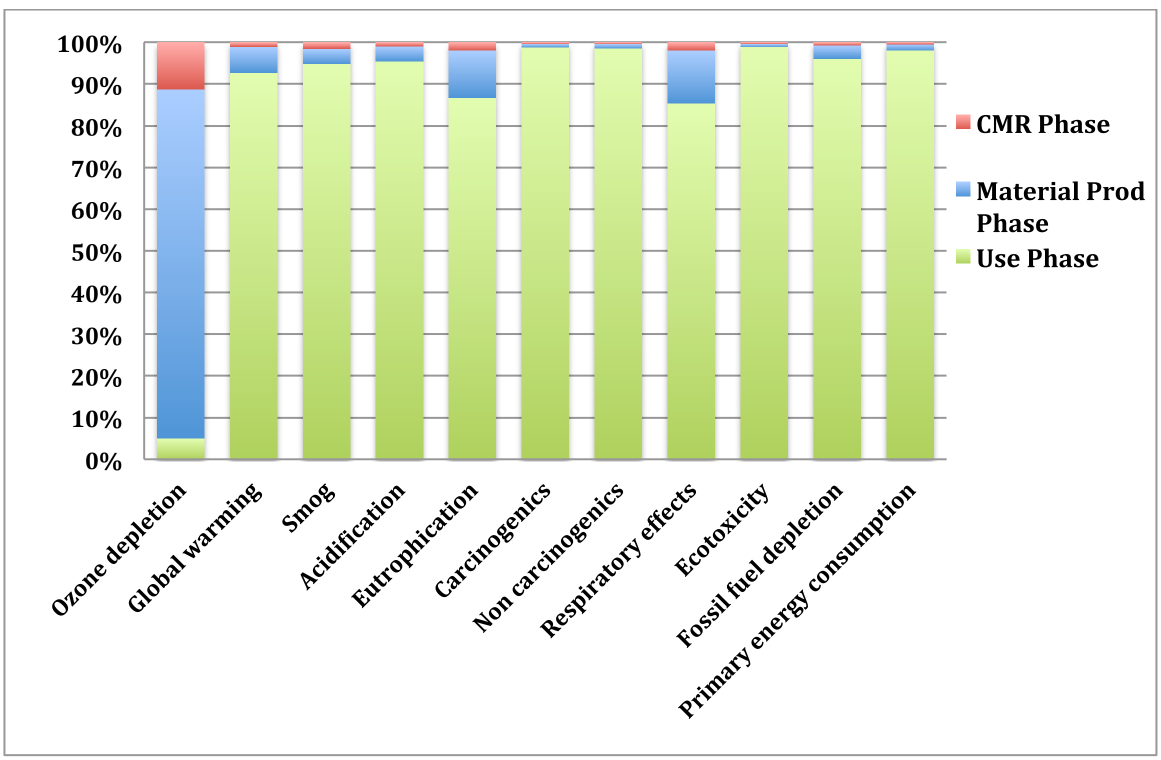
Impact category	Unit	Precast Panel CMR Mat Impacts
Ozone depletion	**kg CFC-11 eq**	2.40E+00
Global warming potential	**kg CO2 eq**	4.87E+06
Smog	**kg O3 eq**	3.08E+05
Acidification	**kg SO2 eq**	3.98E+04
Eutrophication	**kg N eq**	7.52E+03
Carcinogenics	**CTUh**	1.76E-01
Non-carcinogenics	**CTUh**	1.81E+00
Respiratory effects	**kg PM2.5 eq**	3.42E+03
Ecotoxicity	**CTUe**	3.35E+07
Fossil fuel depletion	**MJ surplus**	5.04E+07
Primary energy consumption (renewable + non-renewable)	**MJ**	2.24E+08

5.5.1 Precast Impacts per Phase and Functional Units

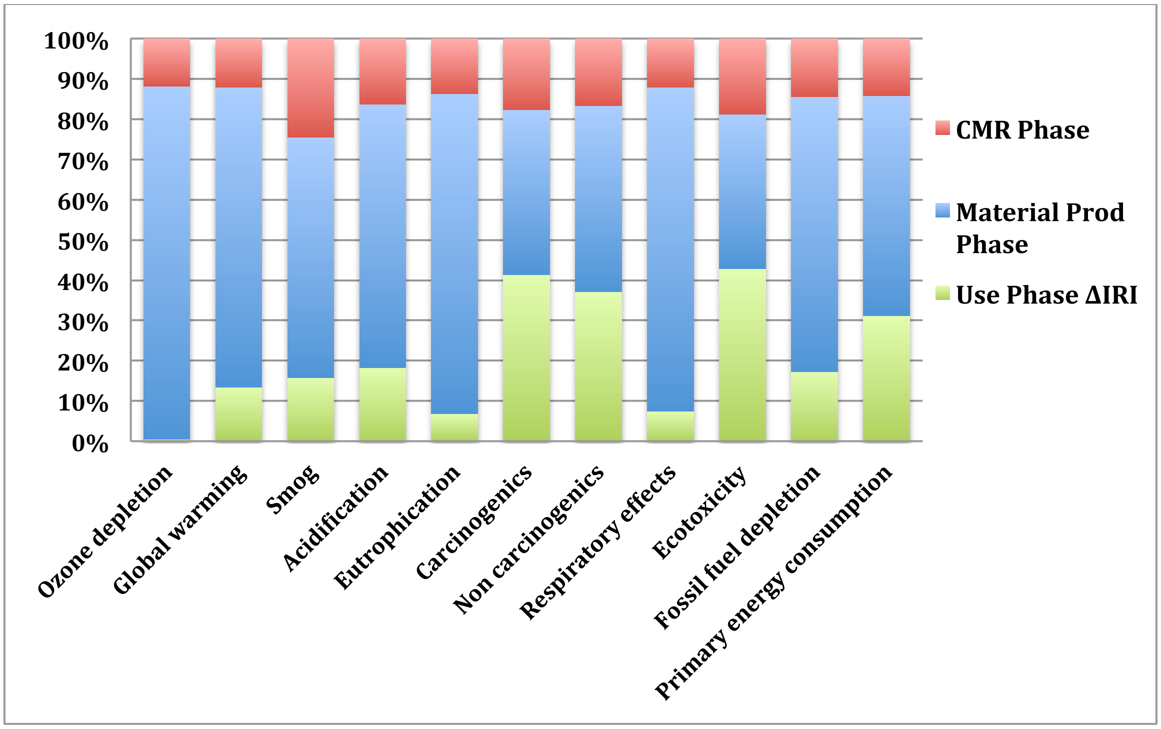
The total impact from each phase was summed and then divided by the functional units for the airport. Table 20 shows the total values for the impacts using both aircraft fuel consumed for one-half the time in flight as well as for only the aircraft fuel consumed due to an increase in IRI. Figure 72a and 71b show the percent contribution from each phase. When only using the fuel consumed by change in IRI, MP phase accounts for about 61%, CMR phase accounts for approximately 17% and the use phase is approximately 22%.

Table 20 - Total Impacts per Functional Units – Precast Panel Case

Precast Panel Case		TW A&B		TW A&B	
Impact category	Unit	Total Impact Per yd^2	Total Impact Per lb-mile	Total Impact Per yd^2 (ΔIRI Only)	Total Impact Per lb-mile (ΔIRI Only)
Ozone depletion	kg CFC-11 eq	6.941E-05	1.362E-17	6.623E-05	1.300E-17
Global warming	kg CO2 eq	2.395E+03	4.700E-10	2.002E+02	3.930E-11
Smog	kg O3 eq	3.013E+02	5.914E-11	1.841E+01	3.613E-12
Acidification	kg SO2 eq	2.660E+01	5.221E-12	1.480E+00	2.905E-13
Eutrophication	kg N eq	1.602E+00	3.143E-13	2.280E-01	4.476E-14
Carcinogenics	CTUh	1.951E-04	3.828E-17	3.906E-06	7.667E-19
Non-carcinogenics	CTUh	1.878E-03	3.686E-16	4.224E-05	8.290E-18
Respiratory effects	kg PM2.5 eq	7.046E-01	1.383E-13	1.110E-01	2.178E-14
Ecotoxicity	CTUe	3.620E+04	7.105E-09	6.951E+02	1.364E-10
Fossil fuel depletion	MJ surplus	2.638E+04	5.178E-09	1.239E+03	2.432E-10
Primary energy consumption (renewable + non-renewable)	TJ	0.18617	3.654E-08	0.00524	1.029E-09



a) percent contribution including time-in-flight fuel consumption
Figure 72 - Phase Impact Contributions – Precast Panel Case



b) percent contribution including only aircraft fuel consumed from change in IRI

Figure 72 (cont.)

5.6 Life Cycle Assessment for Reconstruction

The reconstruction method assumes the PCC, AC base and base course layers are removed and rebuilt. The method for breaking the slabs was a hydraulic hammer on the end of an excavator. It is efficient, rapid and provides enough breakage to allow equipment to removed the debris. Appropriate equipment was selected for the CMR activities as seen in Table 41 and Table 42 (Appendix) for PCC and AC, respectively. Figure 73 shows the fuel consumed for each activity. The highest fuel consumption activities were brooming (112,721 gal), crack sealing (31,072 gal), restriping (16,222 gal) and land clearing (12,328 gal).

Brooming impacts are similar to the rubbilization case study. Crack sealing is slightly less than the rubblization case because the reconstruction (PCC) repair section will not require the same crack sealing as the AC inlay. The most impactful rehabilitation activities were concrete/asphalt demolition, grading after demolition, and concrete/asphalt paving. Theses activities consumed 1,458, 1,135 and 1,848, respectively. The amount of patching is reduced compared to rubblization (same as precast) because of the increased durability of concrete.

The total fuel combusted was one component used to determine the environmental impacts for the CMR phase. Figure 74 shows the percent contribution of fuel for each activity (values are read down the legend and clockwise on the graph). The total fuel consumed for the CMR phase was 205,201 gallons, which is 1,175 gallons more than rubblization and 877 gallons less than precast. The difference between precast and reconstruction is attributed to the speed of demolition and construction. Demolition and the placement of concrete requires less time than the placing of PCPs.

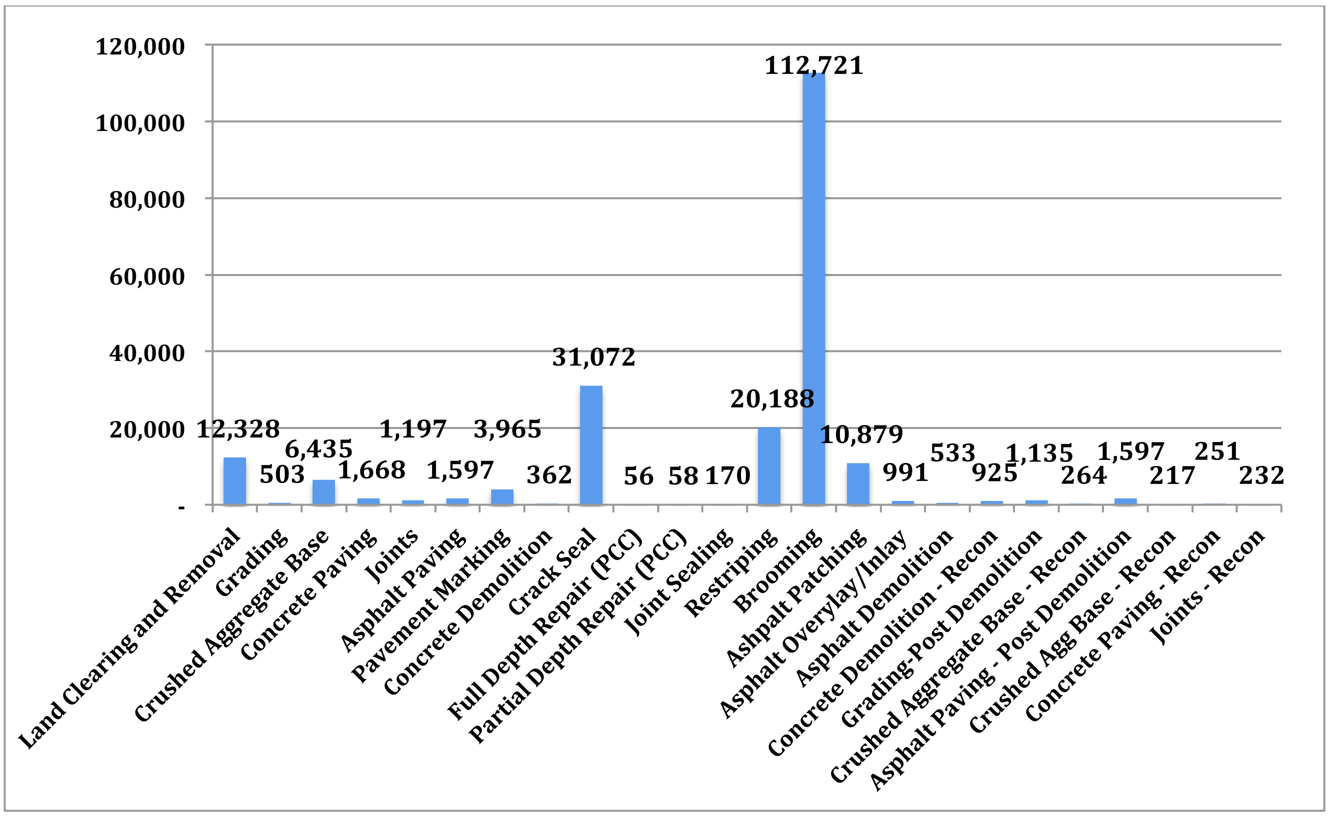


Figure 73 – CMR Fuel Consumption per Activity - Reconstruction

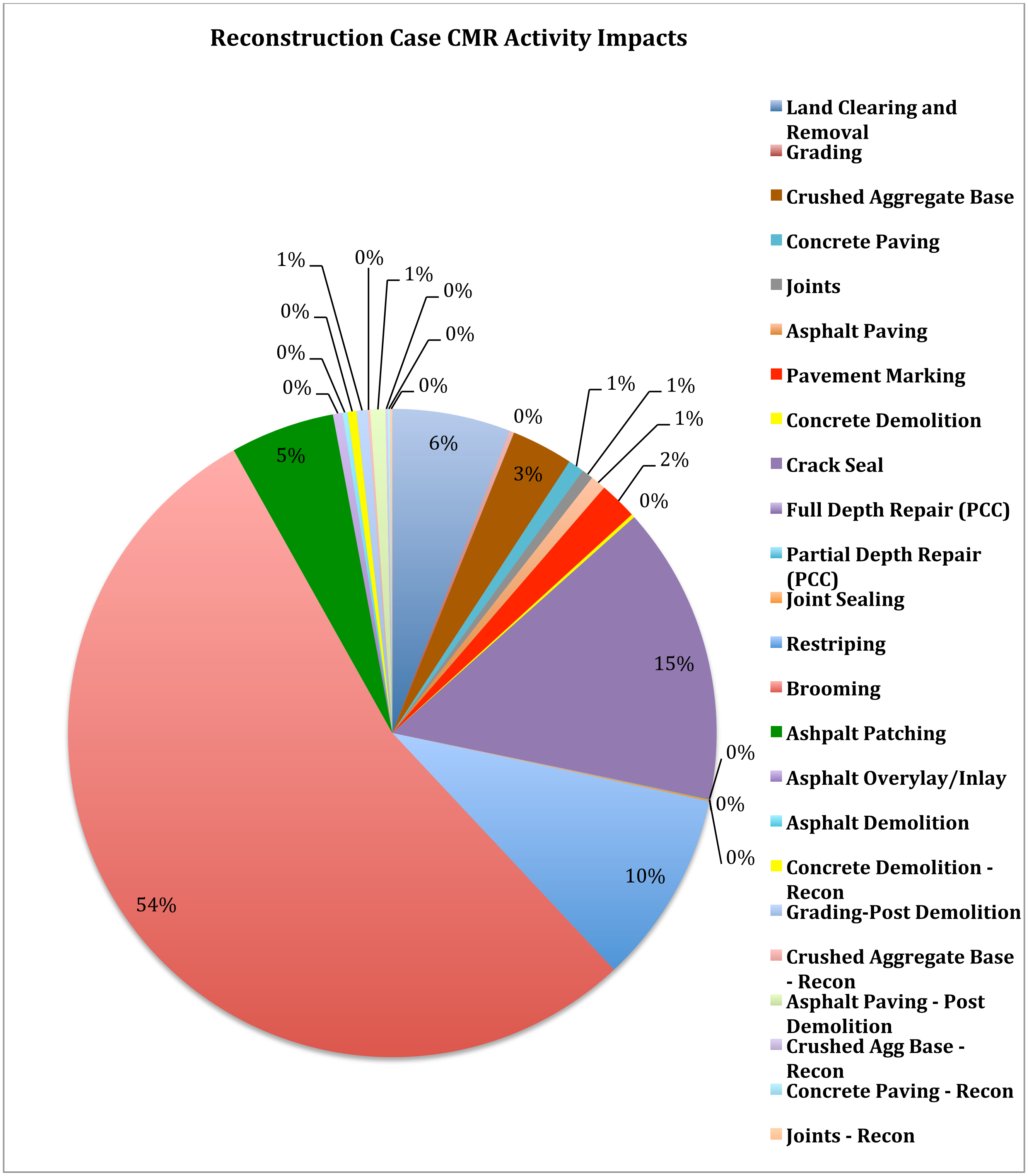


Figure 74 – CMR Fuel Consumption Impact Contribution – Reconstruction

The second component used to determine the total CMR impacts was the materials used in the maintenance and the rehabilitation. As expected, reconstruction had the highest material impacts of all three cases, replacing the full pavement structure to the subgrade. Table 21 the material impacts for the maintenance and the rehabilitation. A 24% increase in energy and a 1% increase in GWP are seen in the reconstruction method compared to rubblization. These increases are 15% and 2% higher than the PCP method

Table 21 - Material Impacts for CMR Phase - Reconstruction

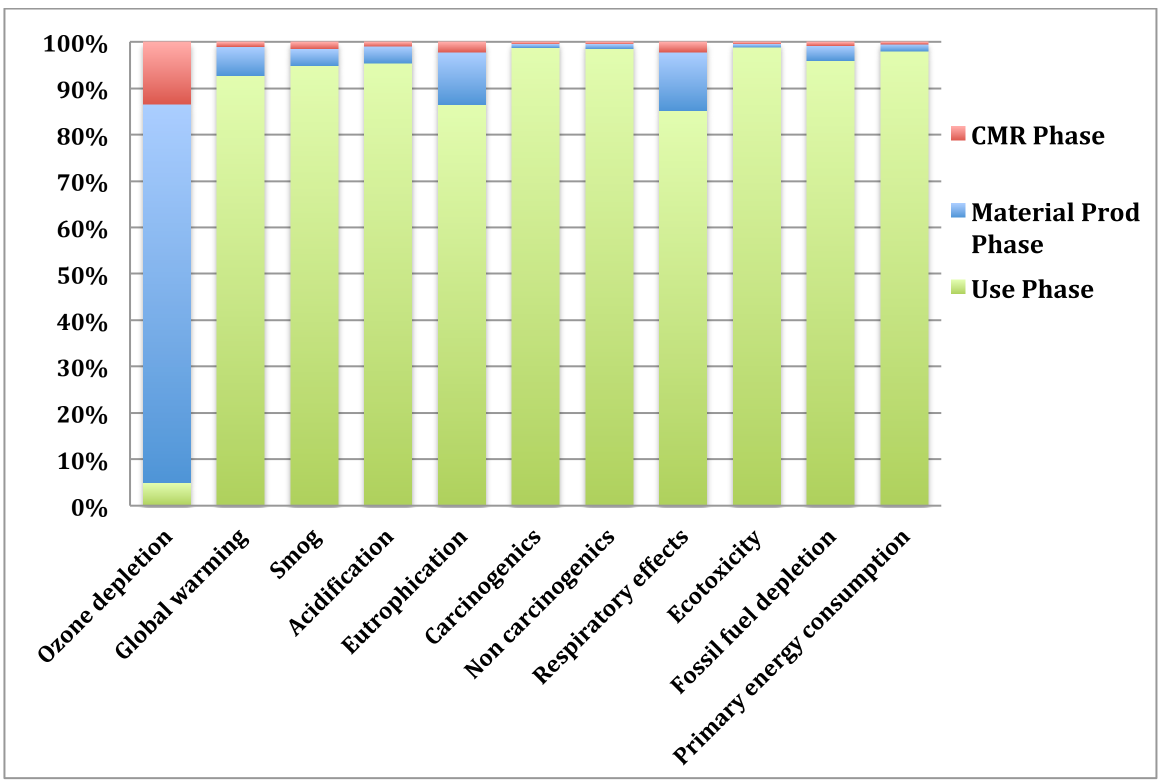
Impact category	Unit	Rubblization CMR Mat Impacts
Ozone depletion	**kg CFC-11 eq**	2.93E+00
Global warming potential	**kg CO2 eq**	4.99E+06
Smog	**kg O3 eq**	3.36E+05
Acidification	**kg SO2 eq**	4.58E+04
Eutrophication	**kg N eq**	8.98E+03
Carcinogenics	**CTUh**	2.15E-01
Non-carcinogenics	**CTUh**	2.20E+00
Respiratory effects	**kg PM2.5 eq**	4.05E+03
Ecotoxicity	**CTUe**	4.17E+07
Fossil fuel depletion	**MJ surplus**	6.22E+07
Primary energy consumption (renewable + non-renewable)	**MJ**	2.55E+08

5.6.1 Precast Impacts per Phase and Functional Units

The total impact from each phase was summed and then divided by the functional units for the airport. Table 21 shows the total values for the impacts using both aircraft fuel consumed for one-half the time in flight as well as for only the aircraft fuel consumed due to an increase in IRI. Figure 75a and 75b show the percent contribution from each phase. When only using the fuel consumed by change in IRI, MP phase accounts for about 60%, CMR phase accounts for 19% and the use phase is approximately 21%.

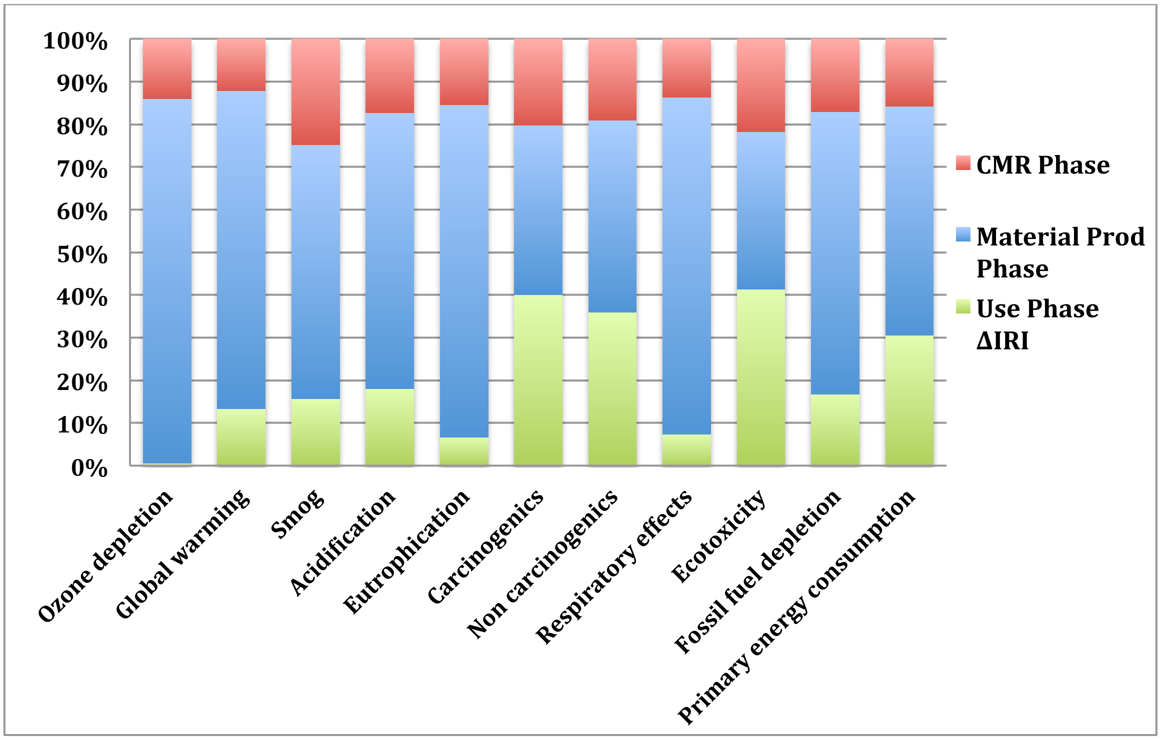
Table 22 - Total Impacts per Functional Units – Reconstruction Case

Reconstruction Case		TW A&B		TW A&B	
Impact category	Unit	Total Impact Per yd^2	Total Impact Per lb-mile	Total Impact Per yd^2 (ΔIRI Only)	Total Impact Per lb-mile (ΔIRI Only)
Ozone depletion	kg CFC-11 eq	7.115E-05	1.397E-17	6.798E-05	1.334E-17
Global warming	kg CO2 eq	2.395E+03	4.701E-10	2.006E+02	3.937E-11
Smog	kg O3 eq	3.014E+02	5.915E-11	1.849E+01	3.628E-12
Acidification	kg SO2 eq	2.662E+01	5.225E-12	1.499E+00	2.943E-13
Eutrophication	kg N eq	1.606E+00	3.153E-13	2.328E-01	4.568E-14
Carcinogenics	CTUh	1.952E-04	3.831E-17	4.034E-06	7.917E-19
Non-carcinogenics	CTUh	1.880E-03	3.689E-16	4.352E-05	8.541E-18
Respiratory effects	kg PM2.5 eq	7.066E-01	1.387E-13	1.130E-01	2.218E-14
Ecotoxicity	CTUe	3.623E+04	7.110E-09	7.216E+02	1.416E-10
Fossil fuel depletion	MJ surplus	2.642E+04	5.185E-09	1.277E+03	2.507E-10
Primary energy consumption (renewable + non-renewable)	TJ	0.18628	3.656E-08	0.00535	1.049E-09



a) Percent contribution including time-in-flight fuel consumption

Figure 75 – Phase Impact Contributions - Reconstruction Case



b) Percent contribution including only aircraft fuel consumed from change in IRI

Figure 75 (cont.)

5.7 Summary for a Rehabilitation LCA of O'Hare International Airport Taxiways A & B

LCA is one of many tools available to airport owners, operators, engineers and contractors to make educated decisions regarding infrastructure investment and their influence on environmental impacts. LCA-AIR was used to evaluate three rehabilitation options consisting of rubbilization with mill/AC inlay, precast panel replacement and full-depth reconstruction for O'Hare International Airport TW A & B. The impacts were normalized to two functional units (square yard and pounds-mile traveled). Each case had the same values for the material production phase (initial construction) and use phase. The construction, maintenance and rehabilitation phase showed differences stemming from the quantity of materials, the construction methods and equipment used in the proposed rehabilitation methods. The rehabilitations at year 30 extended the pavement life to 50 years. The rubbilization with mill/AC inlay required a second AC mill/inlay at year 40 to reach 50 years. The precast panels and reconstruction performance life was an additional 20 years from the time of rehabilitation. The results showed the rehabilitation with the least impact for GWP was as follows: precast concrete panel replacement, rubblization with a mill/AC inlay, and full-depth reconstruction. The ranking of least impact for energy for the three rehabilitation strategies were rubblization with a mill/AC inlay, precast concrete panel replacement, and finally, full-depth reconstruction. The GWP potential for PCP was 2,395 kg CO_2/yd^2 (4.700x10^{-10} kg CO_2/lb-mile), for rubblization was 2,395 kg CO_2/yd^2 (4.310x10^{-10} kg CO_2/lb-mile), and for reconstruction was 2,395 kg CO_2/yd^2 (4.701x10^{-10} kg CO_2/lb-mile). The energy consumed for rubblization was 0.18611 TJ/ yd^2 (3.576x10^{-8} TJ/lb-mile), for PCP was 0.18617 TJ/ yd^2 (3.654x10^{-8} TJ/lb-mile) and for reconstruction was 0.18628 TJ/ yd^2 (3.656x10^{-8} TJ/lb-mile).

CHAPTER 6 – LIGHT DETECTION AND RANGING (LIDAR) & LASER SCANNING

6.1 Definition of LIDAR

Light detection and ranging (LIDAR) equipment sends a light pulse out and measures the time required for the pulse to reflect of an object and return to the receiver instrument. LIDAR is a low power sensor operating in the near-infrared band of the electromagnetic spectrum as seen in Figure 76. Typically they are Class I lasers which are incapable of damaging the human retina (Uddin, 2011; Lasky, Yen, Akin, Lofton, & Ravani, 2010). The operational technology concept is similar to radar or Total Stations. The difference is in the quantity of measurements taken per second. Total station may measure up to eight distances while a LIDAR scan may measure up to half a million distances per second (Lasky, Yen, Akin, Lofton, & Ravani, 2010). Each one of these points contains a specific set of coordinates that can be processed, displayed for visualization, and used for calculations.

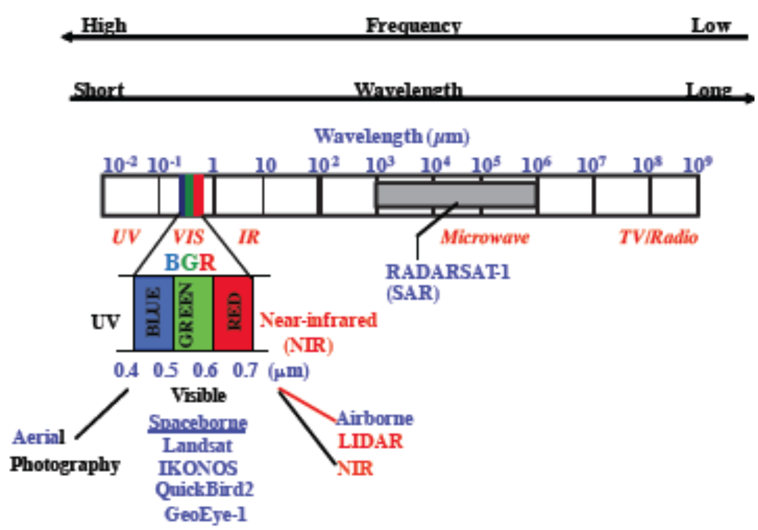


Figure 76 - Wavelength Spectrum and LIDAR Operation
(Uddin, 2011)

6.2 Background and Development of LIDAR

LIDAR was developed in the 1960s for meteorological use (Goyer & Watson, 1963). During the 1970's Apollo 15, 16,17 carried lasers altimeters to provide measurements of the spacecraft's height above the lunar surface. The first information regarding the shape of the moon was gathered by LIDAR (Zuber & Smith, 1996). The deployment of the global positioning system (GPS) in the 1980's allowed LIDAR to become airborne via airplanes and helicopters. The GPS enabled precise location of the airplane and therefore the location of objects reflecting light could be determined. During the 1990's commercial use of airborne LIDAR became increasingly popular. Figure 77 below, portrays a typical airborne LIDAR system consisting of a base station, satellites, airborne vehicle, LIDAR sensors and associated components. Components are discussed in below in Section 3.3.

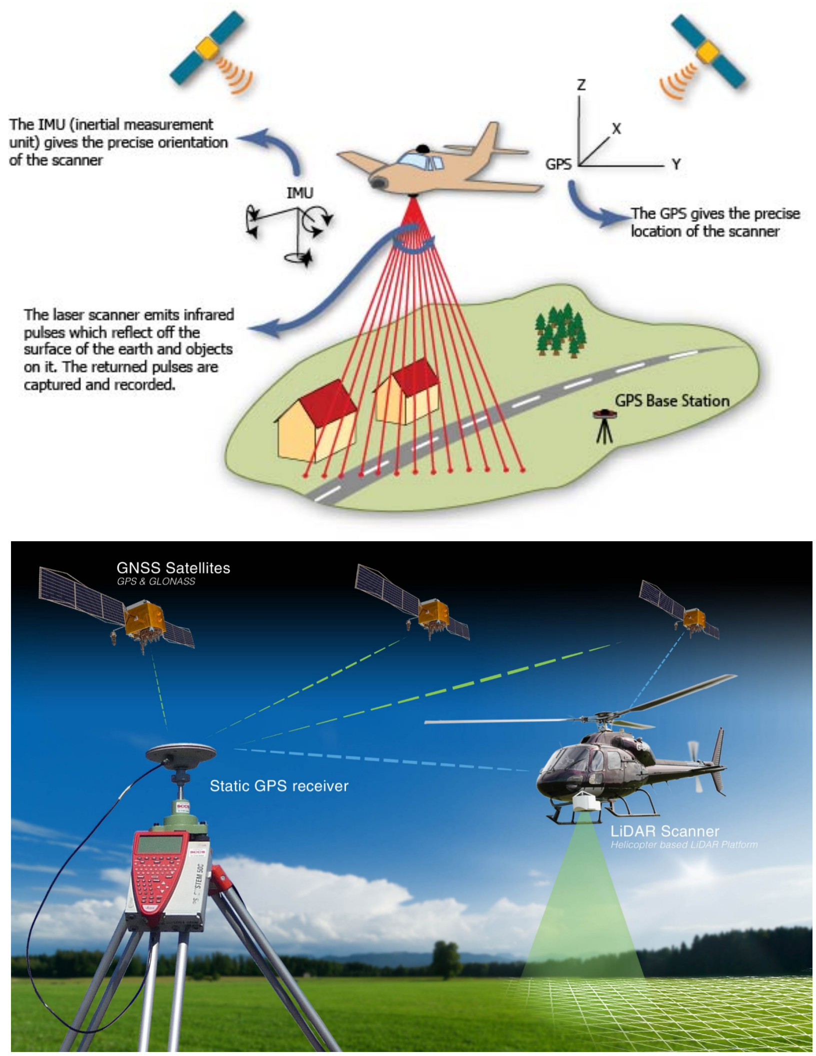


Figure 77 – Airborne LIDAR Visual Setup
(University of Arkansas, 2015; NM Group, 2015)

Shortly after the turn of the 21st century terrestrial LIDAR systems mounted on tripods (Figure 78) became available (National Cooperative Highway Research Program, 2013a). The coverage area of said systems was limited compared to the airborne systems and more economical.

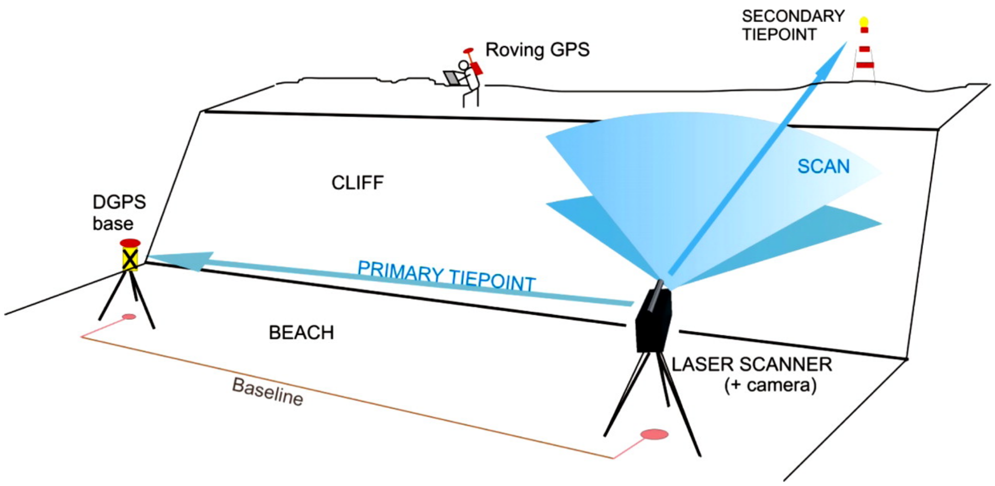


Figure 78 - Terrestrial LIDAR Visual Setup
(Geosphere, 2015)

The cost, time and manpower requirements of using airborne or terrestrial systems should be considered by each agency. To fill the need/void between airborne and terrestrial systems, a mobile LIDAR system was developed.

Advances have been made by placing cameras on vehicles but they initially lacked the 3D depth and coverage desired. In 2003 Terrapoint engineers introduced the first mobile LIDAR system. This was done in Afghanistan to map section of Highway 1 between Heart and Kandahar (~560 kilometers) to reduce the risk of enemy fire from surface to air munitions. The engineers mounted a helicopter LIDAR system to a truck as seen below in Figure 79. This solution worked well with a few limitations. The field of view was limited as the viewing angle is different from the air and from the ground. The view was only 60°, requiring multiple passes. The inertial measurement unit (IMU) was tactical grade requiring limited obstructions for accuracy. The system was mounted on a specific truck and therefore required modification to transfer between vehicles (Glennie, 2007). The value of the system was recognized and multiple commercial manufactures began to develop this technology. Figure 80 below, shows a current mobile LIDAR system. A paper by Yen, et. al. (2011) at the Advanced Highway Maintenance and Construction Technology Research Center discuss multiple models on the market (Yen, Akin, & al, 2011)

Figure 79 - Helicopter LIDAR Mounted to a Truck In Afghanistan
(Newby & Mrstik, 2005)

Figure 80 - Mobile LIDAR System
(Richman & Hogarth, 2010)

6.3 Background and Development of Laser Scanning

Laser scanning for pavements has continually evolved over the years. A big push for laser innovation occurred in the early 2000's from the Long Term Pavement Performance (LTPP) program and issues associated with photographic roadway surveys and associated limitations. The photos did not have consistent quality (resolution), required energy intensive generation of light to illuminate the surface and was affected significantly by the vehicle speed. In 2005 laser-based imaging technology for pavement data acquisition was introduced to capture 1-mm images that were shadow-free. Early systems operated at night with lighting devices to ensure a uniform, shadow-free image was captured. Since 2006 this requirement has been eliminated because a laser light operating in a specific, narrow spectrum in which sunlight has limited interference. A filter is also placed on the camera lens that only allows the light from the narrow laser spectrum to enter (Wang, Hou, & Williams, Precision Test of Cracking Surveys with the Automated Distress Analyzer, 2011; Federal Highway Administration, 2001). The laser scans provided a two dimensional image. From 2005 to 2007 the National Cooperative Highway Research Program (NCHRP) IDEA program funded a team to develop 3D pavement surfaces. This was based on photogrammetric principles, which required similar light conditions for each survey. This created a critical limitation when agencies couldn't use the technology during conditions of sun or low light (Wang, Hou, & Williams, 2011). Often night use was required to maintain the same artificial light source.

Other industries in the 2000's developed a 3D scanning system for conveyor belt systems as seen below in Figure 81. A camera is placed at a different angle to the laser illuminating the object. The vertical elevation changes can be evaluated from the laser lines in the 2D images. These images can be combined to form a 3D digital surface.

Figure 81 - Conveyor Belt 3D Imaging Based on Line Laser Scanning
(Adept Turnkey, 2015)

This method was the adapted by different manufactures for use in pavement scanning. 3D pavement scanning is still evolving with Dr. Kelvin Wang at the Oklahoma State University is heavily engaged in advancing this field. Figure 82, below, shows a typical setup for pavement laser scanning systems. To increase the quality of the image, which is important for distress detail on pavements, often and hybrid 2D/3D system is used. Continued research is being developed for specific applications such as determining the dimensions/quality of airfield pavement grooving.

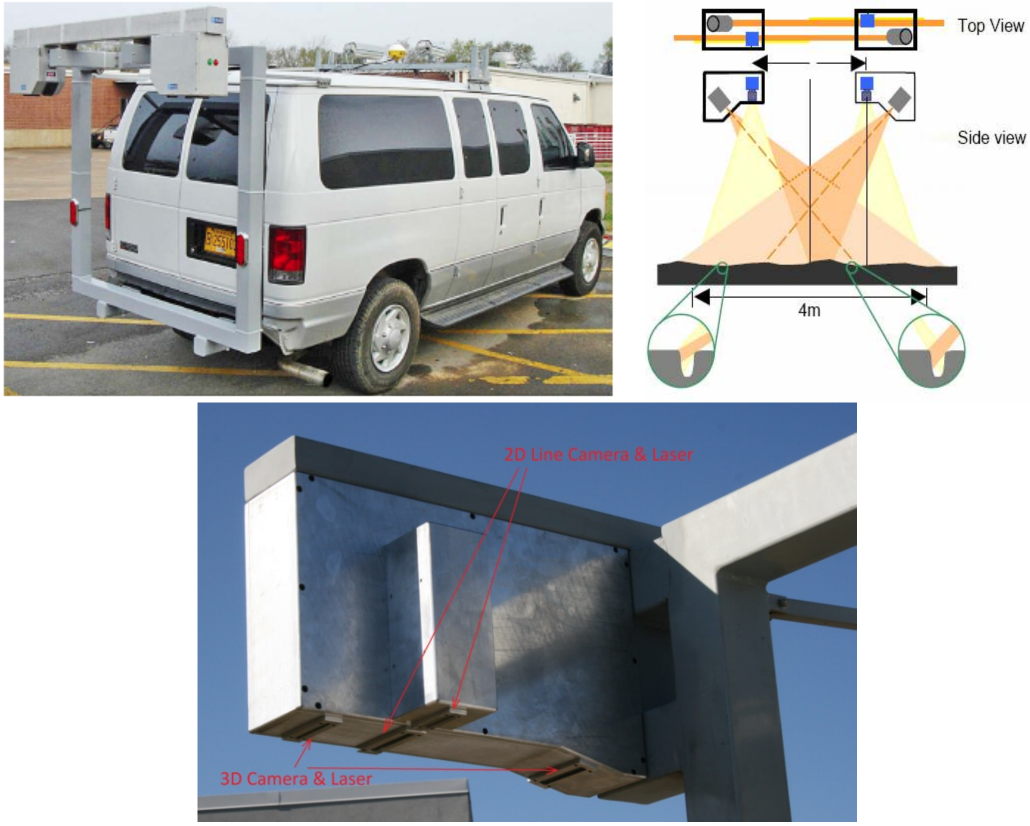


Figure 82 - Laser Scan Vehicle Setup
(Wang & Hou, 2007; Wang, Hou, & Williams, 2011)

After post-processing of the surveys, agencies now can inspect their roadways/airfields from a computer and determine the pavement condition. Like manuals surveys, this is tedious and time consuming but much safer than personnel on the active pavements and more accurate/comprehensive. To save time and money, agencies have developed automated distress analyzer programs. This technology is continuously evolving as equipment and algorithms become more refined. Pavement distresses are geometrically independent and often progress from one type of distress to another. The programming of detection algorithms must be flexible and accurate enough to detect variations in distress. For example, a small crack in the wheel path may be part of a transverse crack that hasn't connected across the width of the pavement. The accuracy of laser scans and crack detection is discussed later in Section 6.7.

6.4 Components of a LIDAR System

Manufactures have different configurations and orientations of the equipment, but the basic components are the same. These include the LIDAR sensors, Global Navigation Satellite System (GNSS) receivers (community of satellites used for global positioning, more commonly referred to as GPS), IMU, distance measurement indicators (DMI), digital cameras and other devices for the operation of the equipment. Figure 83 below, shows a typical setup (Risner, 2014).

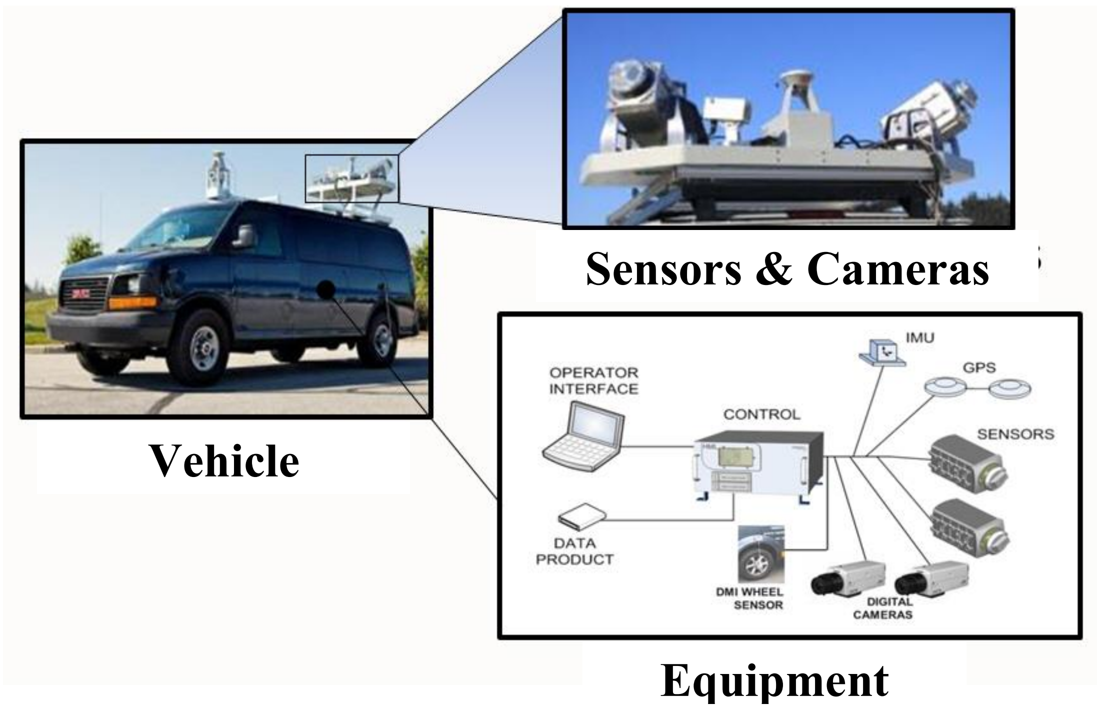


Figure 83 - LIDAR System Components
(Risner, 2014)

6.4.1 LIDAR Sensors

The LIDAR sensors emit pulses or continuous waves at fixed angular increments. They then receive and process these pulses or waves to determine the distance of objects in the field of view. The raw data received consists of angles and rages with time stamps for each pulse or wave. The data is processed and each point contributes to the 3D cloud. The sensors can also measure intensity of each signal. This helps determine the different reflectivity of point in the point cloud or vegetation obstructions. The sensor function is similar to total station sensors but have the capability to process up to half a million points per second.

6.4.2 GPS Receivers

GPS receivers provide three input measurements to the system; time, position (x,y,z coordinates) and velocity (speed and direction). The frequency of positioning is 1 – 10 Hz. The precision is crucial to the accuracy of the point cloud that is generated from the light pulses (National Cooperative Highway Research Program, 2013a).

6.4.3 Inertial Measurement Units (IMUs)

IMUs measure the orientation (roll, pitch and heading). They also assist in position estimation especially when the GPS signal degrades or is obstructed. The frequency of orientation is 100 – 2000 Hz. This increases the accuracy of the final product. A higher frequency is needed as the velocity of the vehicle increases. The GPS and IMU work together to minimize geolocation errors.

6.4.4 Distance Measurement Indicators (DMI)

The DMI is a device typically placed on one of the wheels. It measure tire rotation, which is converted to distance traveled. This supplements the GPS and IMU data.

6.4.5Digital Cameras

Digital cameras may take still images or log video during travel. This aids in the visualization of the point cloud. Due to the spacing of the points, often text on signs or smaller pavement distresses cannot be seen (Yen, Akin, & al, 2011). From the images an RGB color can be attributed to each point. It enables advanced processing of the point cloud. The digital images/pixels can provide greater accuracy than LIDAR points. These images provide a secondary source of information, which is extremely useful in the modeling and presentation of the data.

6.4.6 Ancillary components

Computers and other components provide capabilities to interface/control the equipment, record data and view the data real-time.

6.5 Components of a Laser Scanning System

The components for a laser scanning system are similar to LIDAR components but their purpose and operation is different.

6.5.1 Laser Line Scanners

The systems are equipped with multiple line laser scanners. One set is used with the 2D cameras and the other with the 3D camera to illuminate the pavement surface. This allows data to be collected day or night as long as the pavement is not wet.

6.5.2 2D/3D Cameras

The cameras capture the narrow band of light from each laser illuminating the pavement surface to generate images. As mentioned previously, the 3D camera is at a different angle from the laser in order to detect vertical variations. This combined with the 2D images allows for the creation of a 3D surface.

6.5.3 GPS Receivers

See Section 3.3.1 for description.

6.5.4 Distance Measurement Indicators

See Section 3.3.3 for description.

6.5.5 Ancillary Components

See Section 3.3. 5 for description.

6.6 Spatial Data Lifecycle and Workflow

The use of special data can be placed into four categories; acquiring the data, modeling the data, analyzing the data and applying the data. Figure 84 below, illustrates this continuous cycle. Currently, agencies and organizations across federal and state governments are facing budget reductions and shortfalls. This is particularly true for transportation agencies (National Cooperative Highway Research Program, 2013a). Those agencies and organizations are asked to maintain levels of service or even do more with limited resources. Pavement surveys are time and manpower intensive therefore technology must be leveraged to help bridge the manpower and funding gaps (Qiu & Wang, 2014). LIDAR is an effective method to do so. The development of such a workflow requires an initial investment of time and money. The maintenance crews provide critical knowledge and updates to the workflow once work is completed. This communication and flow of information requires great discipline but the benefits can be continuous.

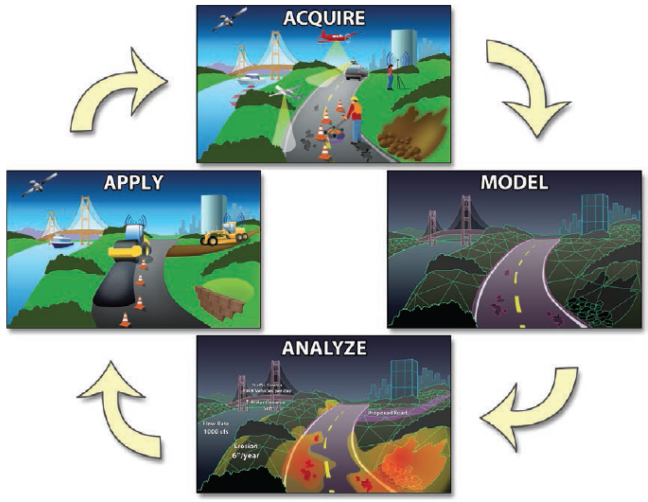


Figure 84 - Spatial Data Lifecycle
(National Cooperative Highway Research Program, 2013b)

6.6.1 Data Acquisition

Past practices for acquiring pavement condition data, asset management, maintenance scheduling, etc. required significant manpower to visit and annalyze the information. Due to human error, the information may change with the person completing the survey. This practice often required closures affecting aircraft operation and profit margins. Significant effort is made to limit the impacts to aircraft operations by preforming surveys at night, which can result in sub-optimal surveys. Regardless of day or night work, if information is missed initially, the team must remobilize, coordinate work/closures to acquire missing data. Additionally, safety is always an issue with aircraft and vehicles operating in the same vicinity. LIDAR and laser scanning minimize or eliminate these issues. Agencies should establish guidelines of when to use mobile systems. Figure 85 shows and example decision tree from the FHWA for mobile system use.

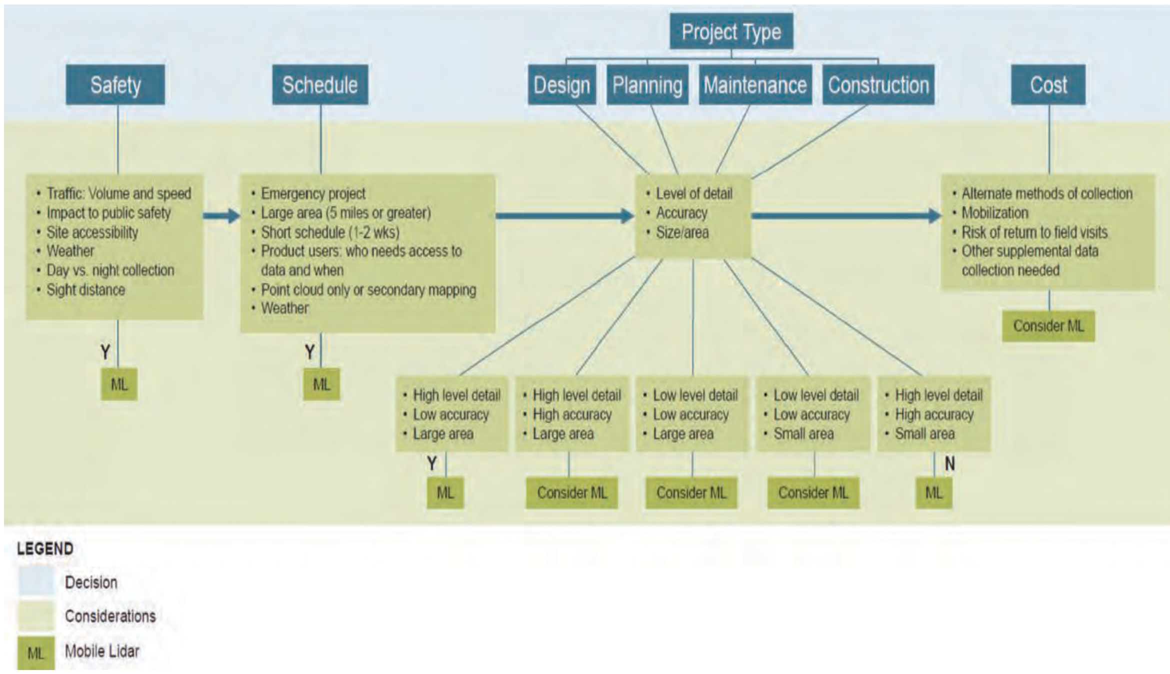


Figure 85 - Mobile System Decision Tree
(National Cooperative Highway Research Program, 2013a)

The use of mobile systems allows data collection of pavement surfaces to occur at highway speeds depending on the level of accuracy or detail required (Wang, Hou, & Williams, Precision Test of Cracking Surveys with the Automated Distress Analyzer, 2011). The data collection can eliminate closures and can be completed with traffic flow or between aircraft operations. This also increases the safety by eliminating requirements for manual (human) inspection on the pavement surfaces. Due to the imaging of the surface, if an area needs to be reviewed, it can be done in the office at the computer eliminating the need for remobilization.

6.6.2 Data Modeling

From the millions of points/images gathered, the data is cleaned and post-processed. This includes the automatic filtering done by the programs (low-level data) as well as the human manipulation (high-level data) of the point cloud. This manipulation requires an individual(s) with geospatial skills (National Cooperative Highway Research Program, 2013a). From the point cloud, a virtual model surface can be constructed. This model provides the user the ability, to view from a computer, any location on the roadway or airfield network. The point cloud or model is used as the basis for the analysis step.

6.6.3 Data Analysis

The quantity of data collected with LIDAR/lasers is high. Table 23 shows the quantity of data generated from an 8-mile stretch of interstate with 2 lanes in each direction with a low accuracy, asset management survey. This may increase up to tenfold using a high accuracy survey (National Cooperative Highway Research Program, 2013c). The data model provides the user the ability to extract the required data for the agencies purposes. This may include but is not limited to pavement distress maps, CAD drawing, GIS data, drainage maps, topography, transverse/longitudinal slopes, asset inventory, etc. The ability to manipulate the collected data is near unlimited.

Table 23 - LIDAR Data Quantity for Oregon DOT

Feature	**Length (miles)**	**Raw Files (GB)**	**Processed Files (GB)**	**Deliverable Files (GB)**	**Totals (GB)**
Mainline	23	40	96	53	**189**
Ramps and Frontage Roads	42	69	108	115	**292**
Totals	**65**	**109**	**204**	**168**	**481**

6.6.4 Application of Data

The outputs from the data analysis can ensure the agencies goals are being met while optimizing the funding. Figure 86 below, was adapted from the NCHRP Report 748 and shows high-level applications for the use of data collected via LIDAR/lasers. The authors of the report broke these categories down as seen in Figure 128, in the Appendix. Many of these applications can be directly applied to airports as well.

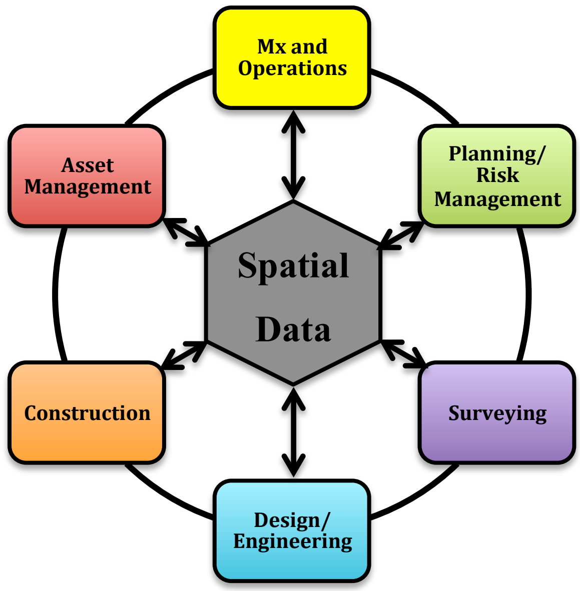


Figure 86 - High-Level Applications for Spatial Data

Due to the size of airports and the different ages of features, managing the assets can be difficult and time consuming. For example, an individual may reference multiple drawings or perform site visits to quantify the number of edge lights or taxiway signs on a runway. From the point cloud, the components can be extracted automatically. This information can be input into a database and associated with different features in GIS, MicroStation, CAD, etc. From the point cloud as-built plans can be generated without sending a survey team to collect or confirm the drawings from decades past.

Another example is for the planning, programing and design of a rehabilitation project. A pavement condition index (PCI) for a particular feature may be 55 based on a selected sample pavement area (i.e. 20 consecutive slabs of the 5000 ft long feature). Based on the PCI, it is time to perform a major rehabilitation of the feature. By reviewing the LIDAR data, only the select area that is contributing to the low PCI should be rehabilitated and the other dollars can be used elsewhere. Funding dollars are extended to maintain/increase levels of service for the airfield. Maintenance and operations teams benefit as well. With the comprehensive survey done by LIDAR/lasers, a complete picture is generated and materials and labor can be focused on the most critically distressed areas as opposed to 'hurry-up' repairs. It is understood that FOD will always be an issue and will require immediate attention. However, reactive maintenance will shift to preventative maintenance, which is more effective, economical and predictive.

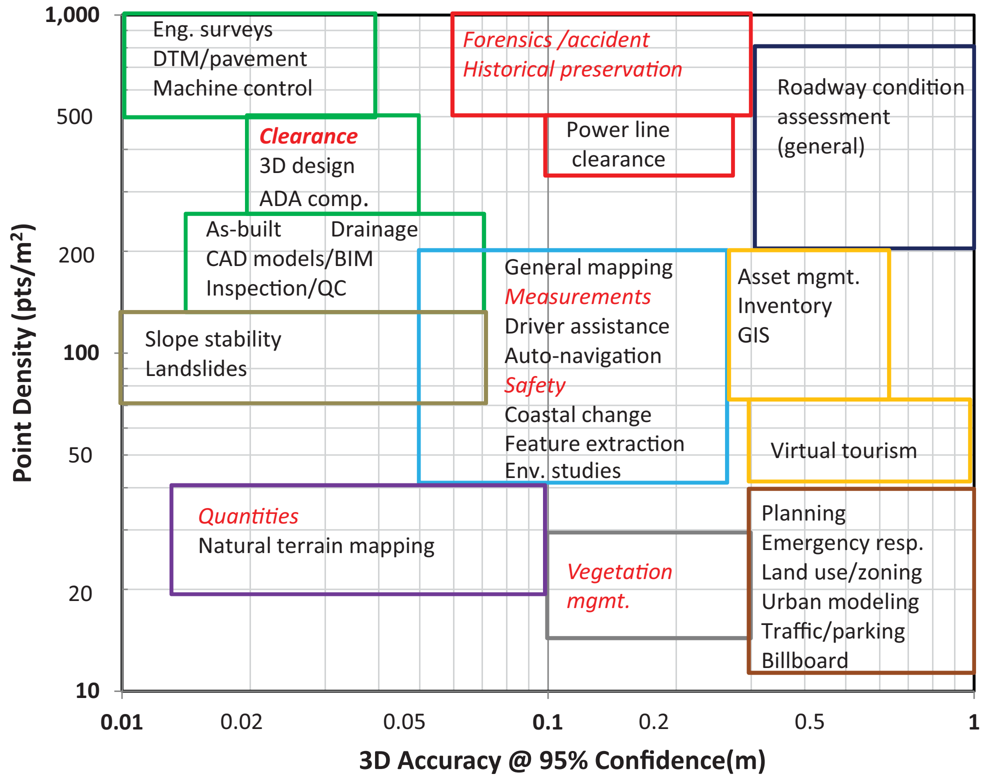
Funding arenas are very competitive and require solid justification for projects. The LIDAR data and associate results provide rapid, detailed and accurate information for project justification. This data can also assist in the long-range development plan and posture the agency for funding in future fiscal years. Utilizing the data collected empowers an agency to make better and more efficient decisions, now and in the future.

6.7 Accuracy of LIDAR and Laser Scanning

The value of the data is only as good as accuracy for the specific project. Different projects have different levels of accuracy. Cracking in pavement requires a high level of accuracy while the accuracy for asset management is much lower. LIDAR accuracy has a larger variation because of many uses. Laser scanning is very specific to pavements and the accuracy variation stems only from changes speed of the vehicle.

6.7.1 LIDAR Accuracy

LIDAR accuracy is a function of the point density. The greater number of point per square unit, the greater the accuracy. Figure 87 below, shows recommended point densities from NCHRP Report 748 for a multitude of projects. Figure 88 below, shows the accuracy associate with point densities. The current accuracy limitation for LIDAR is one-quarter inch for objects closer than approximately 50 m as seen below in Figure 89. This accuracy will not capture all the distresses on a pavement or assist in quantifying distress growth over time. Due to this limitation camera imagery supplements this data for technicians to evaluate on a computer screen (Risner, 2014).



Note the use of a log scale on both axes.
Network accuracies may be relaxed for applications identified in red italics.

Figure 87 - Recommended LIDAR Point Densities for Specific Projects
(National Cooperative Highway Research Program, 2013a)

Accuracy	HIGH < 0.05 m (< 0.16 ft)	MEDIUM 0.05 to 0.20 m (0.16 to 0.66 ft)	LOW > 0.20 m (> 0.66 ft)
Density	**1A**	**2A**	**3A**
FINE >100 pts/m^2 (>9 pts/ft^2)	• Engineering surveys • Digital terrain modeling • Construction automation/ Machine control • ADA compliance • *Clearances** • *Pavement analysis* • Drainage/Flooding analysis • Virtual, 3D design • CAD models/Baseline data • BIM/BRIM** • Post-construction quality control • As-built/As-is/Repair documentation • Structural inspections	• *Forensics/Accident investigation** • *Historical preservation* • Power line clearance	• Roadway condition assessment (general)
	1B	**2B**	**3B**
INTERMEDIATE 30 to 100 pts/m^2 (3 to 9 pts/ft^2)	• Unstable slopes • Landslide assessment	• General mapping • *General measurements* • Driver assistance • Autonomous navigation • Automated/Semi-automatic extraction of signs and other features • Coastal change • *Safety* • Environmental studies	• Asset management • Inventory mapping (e.g., GIS) • Virtual tourism
	1C	**2C**	**3C**
COARSE <30 pts/m^2 (<3 pts/ft^2)	• *Quantities (e.g., earthwork)* • Natural terrain mapping	• *Vegetation management*	• Emergency response • Planning • Land use/Zoning • Urban modeling • Traffic congestion/ Parking utilization • Billboard management

**Network accuracies may be relaxed for applications identified in red italics.*
**BIM/BRIM: BIM = Building Information Modeling; BRIM = Bridge Information Modeling.
These are only suggestions; requirements may change based on project needs and specific transportation agency requirements.

Figure 88 - LIDAR Accuracy Based on Point Densities for Specific Projects
(National Cooperative Highway Research Program, 2013a)

Maker	Optech	Riegl	Riegl	Z+F	Phoneix Sci	Sick	Sick	Faro	Velodyne	Velodyne
Photo										
Model	Lynx V200 Lynx M1	LMS-Q120i	VQ-250	5010 Imager / Profiler	PPS-2000	LMS291	LMS511	Focus 3D	HDL-64E	HDL-32E
Range Accuracy	+/- 7 mm (1 σ) (0.02 ft)	20 mm (0.07 ft)	10 mm (0.03 ft)	~ 3 mm (0.01 ft)	0.15mm (0.05 ft)	+/- 35 mm (0.11 ft)		~ 3 mm (0.01 ft)	+/- 15 mm (0.05 ft)	+/- 20 mm (0.07 ft)
FOV (degree)	360	80	360	320	90	180 or 90	190	305	360	360
Scan Freq.	80-200 Hz	100 Hz	100 Hz	Imager: 50 Hz Profiler: 100 Hz	1000 Hz	75 Hz	100 Hz	97 Hz	15 Hz	5-20 Hz
Long Spacing @ 55mph	0.12 m (0.4 ft)	0.25 m (0.8 ft)	0.24 m (0.8 ft)	0.16 m (0.8 ft)	0.03 m (0.08 ft)	0.32 m (1 ft)	0.24 m (0.8 ft)	0.24 m (0.8 ft)	0.03 m (0.8 ft)*	0. m (0. ft)**
Point/s	Up to 500,000	10,000	Up to 300,000	1,016,000	945,000	13,500	19,000	Up to 976,000	1,000,000	800,000
Practical Range	~ 75 m	~ 50 m	~ 75 m	~ 50 m	~ 3 m	~ 25 m	~ 40 m	~60 m	~ 75 m	~ 75 m
Eye Safety	Class 1, Yes	Class 1, Yes	Class 1, Yes	Class 1, Yes	Class IIIb, No	Class 1, Yes	Class 1, Yes	Class 3R, Yes	Class 1, Yes	Class 1, Yes
Multi-return	Yes	No	Yes	No	No	No	Yes	No	No	Yes
Cost	~ $200,000	N/A	~ $200,000	~ $150,000	N/A	~ $5,000	~ $5,000	$40,000	$75,000	$30,000
Website	Optech.com	Riegl.com	Riegl.com	Zf-laser.com	Phnx-sci.com	Sickusa.com	Sickusa.com	Faro.com	Velodyne.com/ lidar	Velodyne.com/ lidar

Figure 89 - LIDAR System Data
(Yen, Akin, & al, 2011)

6.7.2 Laser Scanning Accuracy

Laser scanning for pavements is a specific technology with high accuracy. Current accuracy is a function of the vehicle speed and the equipment capture rate. Laser scanning accuracy range from 0.5 mm at 30 mph to 1 mm at 60 mph in both the horizontal and vertical directions (Wang, Hou, & Williams, 2011; Qiu & Wang, 2014).

Wang et al. (2011) utilizes their Digital Highway Data Vehicle (DHDV) and their Automated Distress Analyzer (ADA) to determine the crack map and generate the UK SANNER Index. They then compared three different methods to evaluate the precision and accuracy of an automated cracking survey, a semi-automatic survey (automated survey plus manual review using the MHIS Deluxe software) and a manual processing survey (viewing the images via the MHIS Deluxe software without and preprocessing, Figure 90) from three statistically similar raters.

Wang et al. (2011) evaluated 20 asphalt pavement sections, each 160 m in length with pavement condition ranging from good to poor. The manual survey took an average of 64 minutes per section. The semi-automatic took an average of 28 minutes per section. The automatic survey took 16 seconds/section. The fully automated results were statistically acceptable for 90% of the sections, just being slightly lower for two sections (#1 and #11) as seen below in Figure 91. The semi-automatic results were acceptable for all sections as seen below in Figure 92. Based on the results, semi-automatic surveys provide similar accuracy as manual surveys while saving more than 50% in time. For large area networks, automated surveys provide a more comprehensive survey than traditional methods and are worth the investment. automoated surveys require continued development to increase accuracy of the results (Wang, Hou, & Williams, 2011).

Figure 90 - MHIS Deluxe Software Interface
(Wang, Hou, & Williams, 2011)

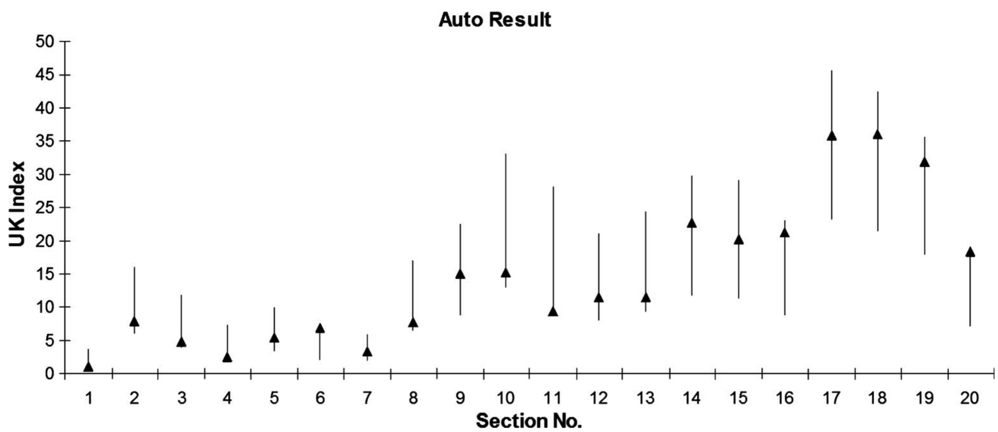


Figure 91 - Automatic Results (triangles) Compared to Manual Results (range - vertical lines)

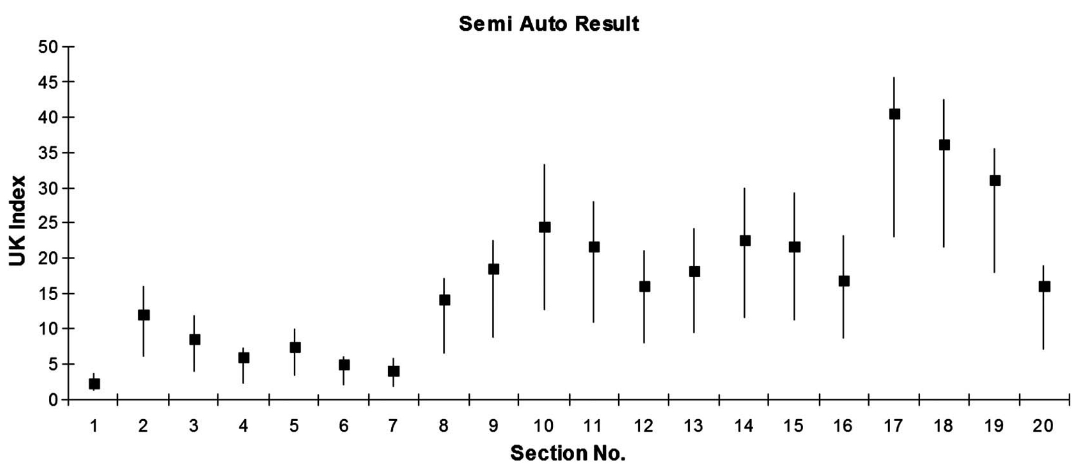


Figure 92 - Semi-Automatic Results (squares), Compared to Manual Results (range - vertical lines)
(Wang, Hou, & Williams, 2011)

6.8 LIDAR and Laser Scanning for Airfields

LIDAR/lasers proven use on highway systems and airfield's increased demand for time and money saving technology to minimize operational impacts has opened the field for new geospatial opportunities. Geospatial technology is a powerful tool for airfield owners, operators, and staff to use because of the large quantities of assets/ages (pavements, lights, markings, signs, etc.), short work windows, stringent safety requirements, operational considerations, and the need for multi-year data collection. LIDAR has greater flexibility than laser scanning because of the data capturing technique and more general use. Laser scanning was specifically designed to analyze pavement distresses and does this function well. This section will discuss four uses for this technology.

Mobile systems need to perform multiple passes because of the large pavement areas and adjacent assets. This should be factored into the time requirements. Figure 93 below, shows a sample of runway and taxiway drive paths performed by the mobile system at George Bush Intercontinental Airport for a pavement distress survey. The operators averaged 25 miles per 8-10 hour days. After field collection the data is cleaned, stitched together and processed as seen below in Figure 94. This may take anywhere from two to five times longer than the field time depending on the deliverable variables (Hiremagalur, Yen, Akin, Bui, Lasky, & Bahram, 2007).

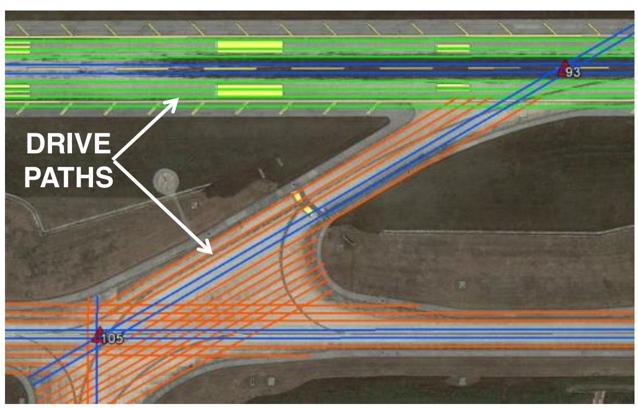


Figure 93 - Mobile System Drive Paths
(Risner, 2014)

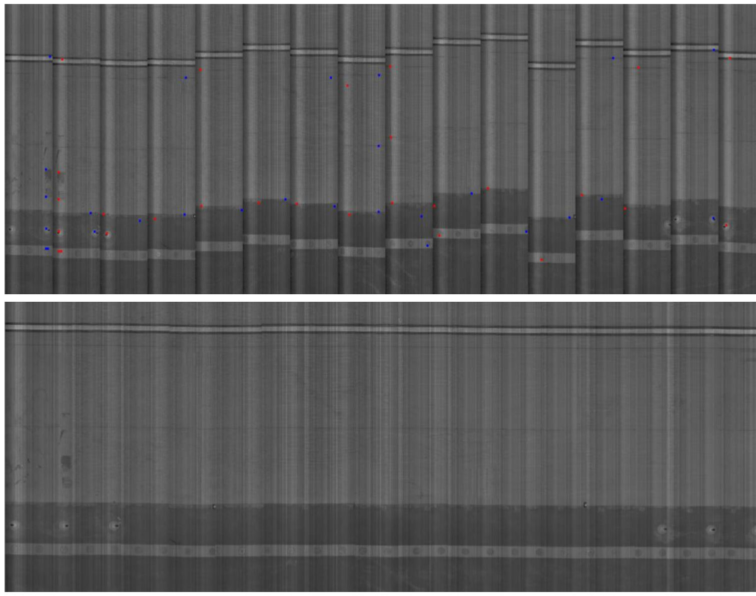


Figure 94 - Image Stitching for Multiple Passes - Unstitched (top) and Stitched (bottom)
(Wang K. C., 2015)

Figure 95 below, shows the two types of data collected during and airfield survey; point cloud and a digital image. Both are necessary for effective post processing. Figure 96 below, shows a combined image for a LIDAR survey. The point cloud is processed and colorized to help with the visualization. Some distresses are difficult to see from just the point cloud, as maximum accuracy is one-quarter inch. Therefore, geo-referenced imagery is stitched together with the point cloud. At this point, algorithms can highlight or better define the edges of various airfield features as seen in green and blue. These algorithms can be used create the deliverables such as determine areas, quantities, etc. for different features. Laser scanning provides a higher quality image (1 mm resolution) even without digital images. Laser images are shown and discussed in depth below.

Figure 95 - (Left) LIDAR Point Cloud (Right) Digital Image
(Uddin, 2011)

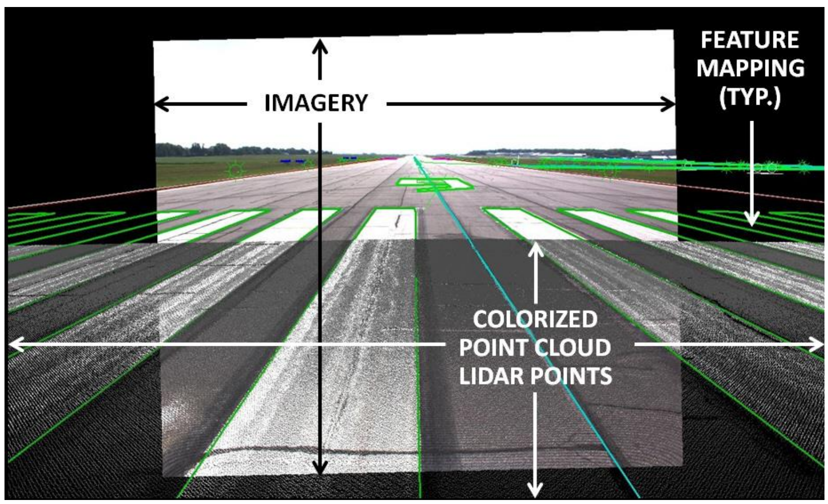


Figure 96 - LIDAR Data Output Example
(Risner, 2014)

6.8.1 Condition Survey and Distress Mapping

Condition surveys are important to airport owners and the aircraft transverse use them. Pavement distresses negatively impacts the aircraft operations. Increased distresses and pavement roughness directly impacts the aircraft components potentially causing higher aircraft maintenance. For pavements, increased roughness and irregularities increase pavement layer stresses, which propagate the roughness and decrease the performance life (Barbarella, De Blasiis, Fiani, & Santoni, 2014). PCI surveys help identify areas in need of repair or rehabilitation to ensure design life is achieved and ensure the aircraft can operate safely. PCI surveys require large amounts of time, manpower and closures. Additionally, only a small portion of each feature is sampled and is deemed representative of the entire feature (RW, TW, apron, etc.).

With LIDAR/lasers, a comprehensive survey can be complete with minimal impacts to operations. The distresses can found manually or via automated algorithms. Figure 97 below, shows a colorized point cloud with distresses from LIDAR. Larger cracks are easily visible. However, some cracks are much smaller and will require additional manual processing and supplemental imagery to ensure they are captured. A good illustration of this is seen in a static LIDAR scan of a concrete pavement in Figure 98. As the crack size decreases it becomes difficult to see where the crack ends. This is a limitation for LIDAR especially when used with automated distress detection algorithms. Currently, no algorithm is perfect, but automatic crack detection is more developed than other distress types (Wang K. C., 2015). Therefore, a technician must verify and mark other distresses as shown below in Figure 99.

With the distresses marked and classified GIS/Microstation mapping can be created as seen below in Figure 100. A PCI can be provided for every square foot of each feature. This map can be used to refocus maintenance operations, establish multi-year funding plans or be overlaid with other non-destructive testing data (LTE, traffic density, etc.) to solve distress issues. These distresses can also be input in to MicroPaver or similar pavement management systems (PMS) (Nelson, 2014).

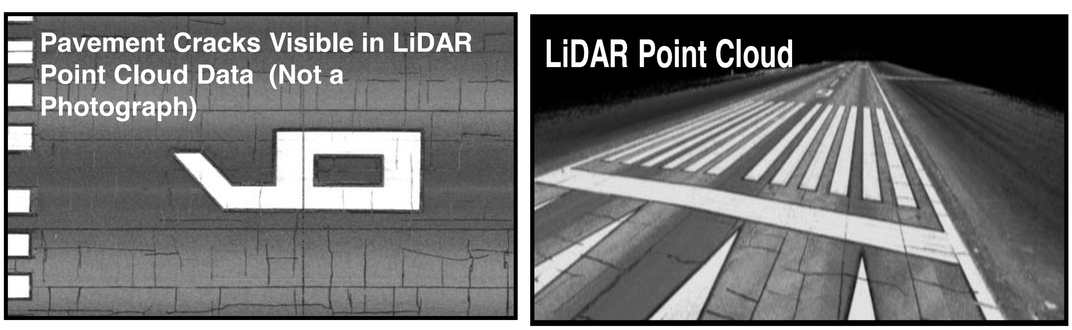


Figure 97 – LIDAR Point Cloud for Runway
(Risner, 2014)

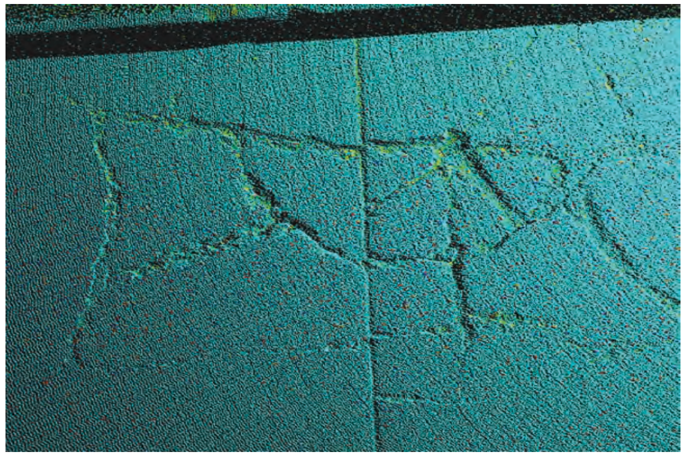


Figure 98 – LIDAR Intensity Scan of Concrete Pavement
(National Cooperative Highway Research Program, 2013a)

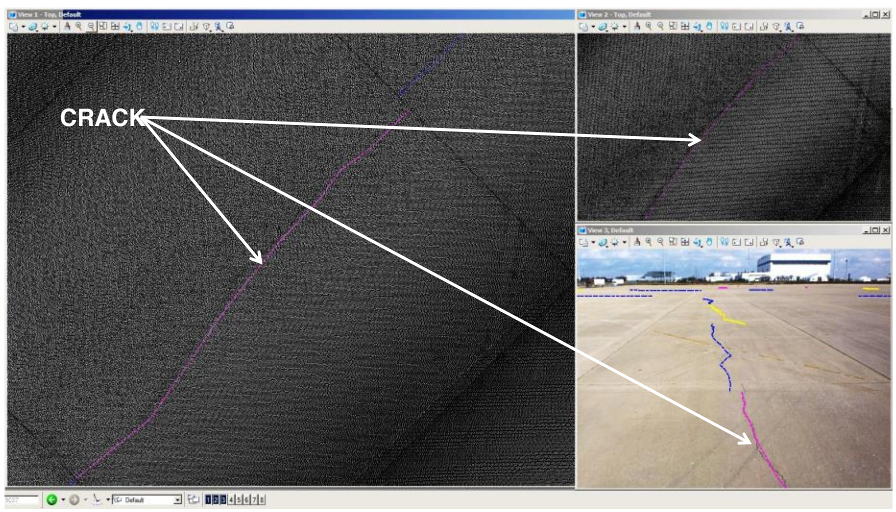


Figure 99 – LIDAR Data Crack Detection
(Risner, 2014)

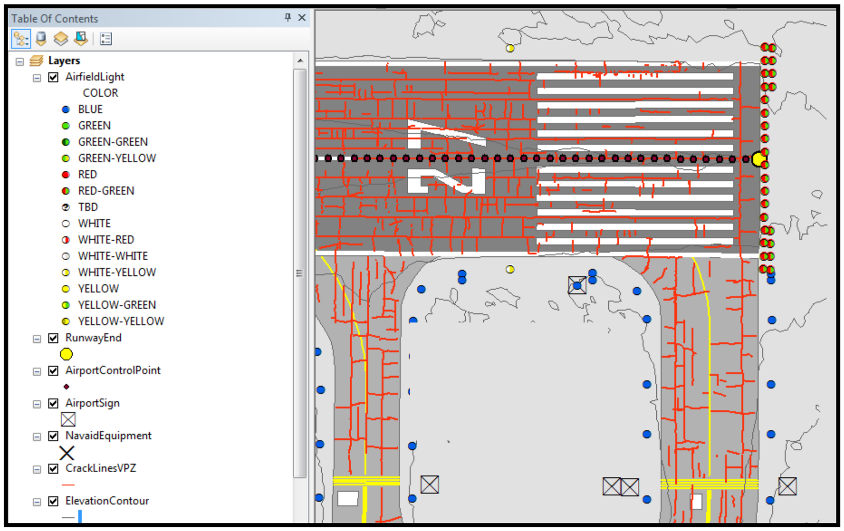


Figure 100 – Pavement Distresses Mapped in GIS
(Risner, 2014)

6.8.2 Topography and Hydraulics with LIDAR

Another deliverable of LIDAR is the topography and profiles of the pavement feature. Utilizing total stations is time consuming but advances in GPS technology allow technicians to carry a roaming device and collect points fairly rapidly. Topographic maps, transverse, longitudinal profiles and digital elevation models can be generated from the collected points. Figure 101 below, shows the outputs from a standard tachymetric survey. The models are dependent on the points collected and interpolation between two sets of points. This data can be used to verify as-built conditions or to develop hydraulic models. LIDAR and lasers allow for this data to be collected continuously and therefore more realistic elevation models. Figure 102 below, shows a contour map for Highway 113 captured via LIDAR with a contour spacing of about 10 cm. Similar maps can be generated for airfields. These maps and associated information (elevation, slopes, etc.) can feed into storm water management plans and hydraulic modeling. A point density greater than 150 pts/m^2 will provide sufficient accuracy for a surface hydraulic model.

Specific area maps can be developed to evaluate drainage issues in the absence of as-built elevation data. Figure 103 below, shows staining on the pavement surface from ponding water. LIDAR was used to determine the elevation discrepancies that then can be used to design a repair strategy for the drainage issue.

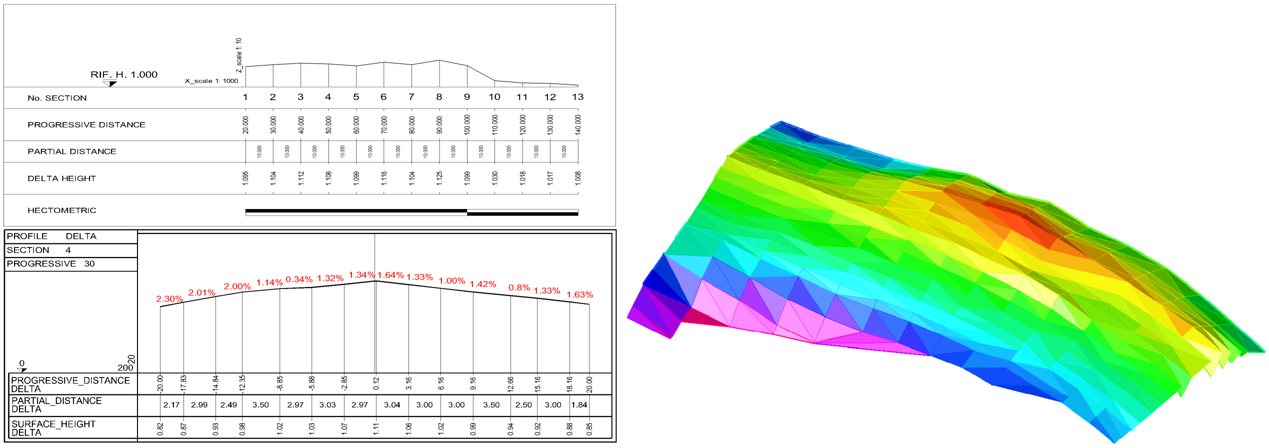


Figure 101 - Transverse, Longitudinal and Digital Elevation Model of a 200m Taxiway Section
(Barbarella, De Blasiis, Fiani, & Santoni, 2014)

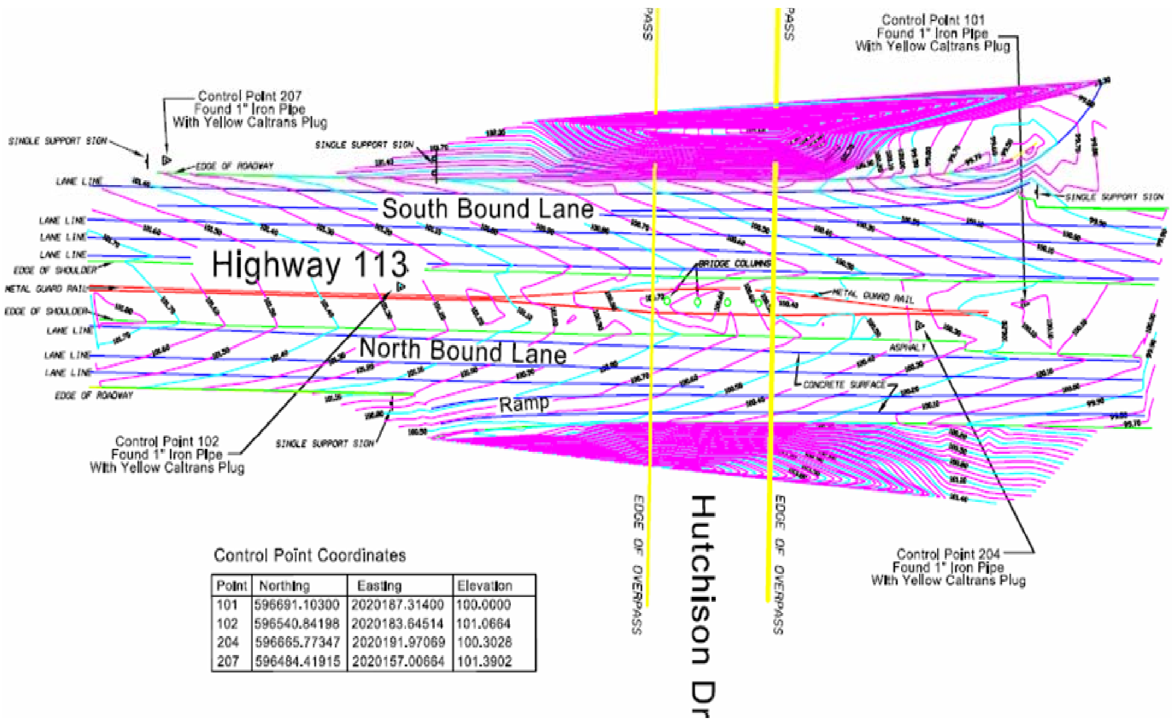


Figure 102 - Topographic Map of a Section of Highway 113 (~10 cm spacing)
(Hiremagalur, Yen, Akin, Bui, Lasky, & Bahram, 2007)

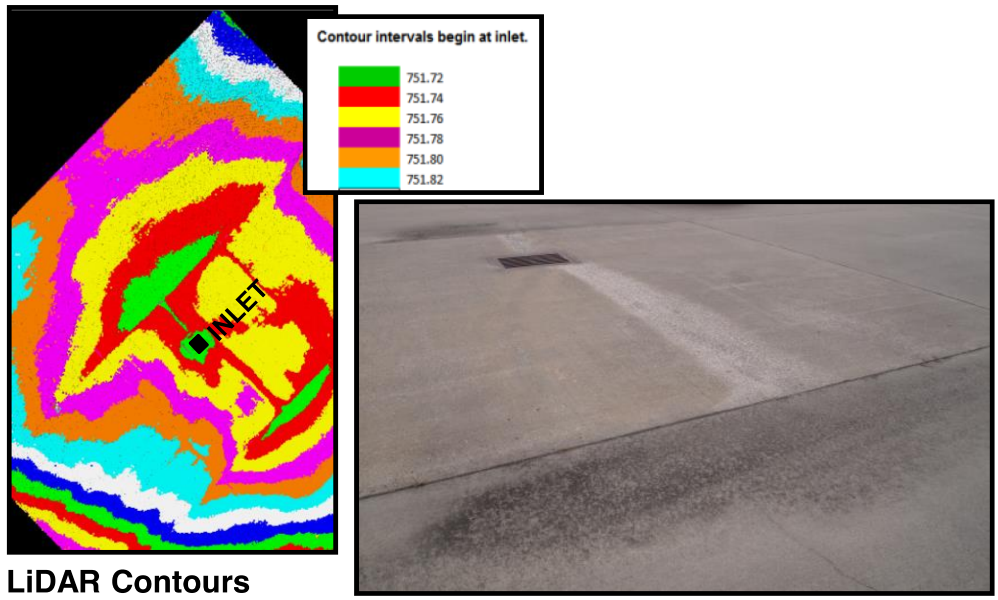


Figure 103 - LIDAR Contours at Drain Inlet (Identifies Ponding)
(Risner, 2014)

6.8.3 Profile Measurements

A pavements cross slope is extremely critical to the water removal and safe operation of aircraft. Rough longitudinal profiles can have a large impact on the wear/fatigue of aircraft components and passenger comfort and safety. Profile measurements are commonly collected by single/multi-point lasers or electronic levels (manual). The laser profilers for roadways come in light (walk-behind), medium (utility/all terrain vehicles) and heavy weight (vehicle) (Wang H. , 2006). Each has specific uses, but single point lasers only accurately reflect one point on the pavement surface while lacking a comprehensive coverage that can miss critical areas. Multi-point laser profiling systems have significant more coverage than single point lasers but lack complete lateral coverage as seen in Figure 104. The manual electronic level measurement is time consuming, dangerous and cannot be accomplished for the whole pavement feature (Tsai, Ai, Wang, & Pitts, 2012).

Figure 104 - Multi-Point Profiler
(PaveTesting, 2015)

The spatial accuracy of LIDAR was compared to a National Geodetic Survey on a runway in Virginia. The goal was to verify the accuracy of the mobile LIDAR system and show the ability to precisely map a runway's surface. For this survey the vertical accuracy was with in 10 mm of digital levels from a Real Time Kinematic (RTK) GPS survey. 1204 test points were compared by each method and the elevation differences analyzed. Figure 105 below, shows and excellent correlation between the two surveys with an R-value of 0.999. The use of LIDAR for profile (longitudinal and transverse) is rapid and accurate.

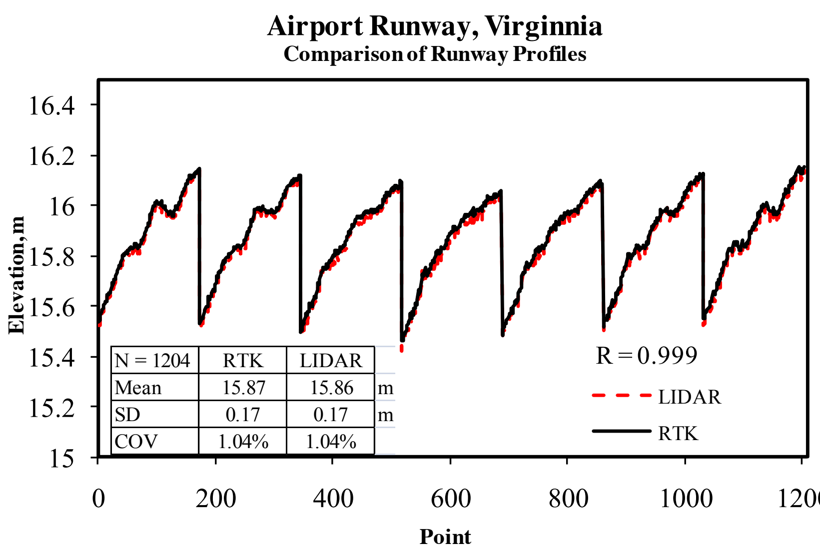


Figure 105 - Runway Elevation Comparison Between GPS and LIDAR Survey
(Song, Profile Data Comparisons for Airfield Runway Pavements, 2014)

6.8.4 Asset Management

In addition to millions of square feet of pavement surfaces, airports have hundreds of signs, thousands of edge lights and many other assets to manage. Ideally, in larger projects, each of these features is identified on as-built drawings (hard copy and electronic CAD, GIS, etc.). However, with time under the rush to make a repair or provide greater clarification, new features are added which don't make it into the drawings. LIDAR has the ability to locate and map such assets (Lane & Cumore, 2014). Figure 106 below shows a point cloud with the edge lights identified. Rapid identification of quantities and location of assets can be assessed and imported into GIS/MicroStation/CAD. Utilizing the data can benefit request for proposals. For example, the total quantity of paint required for restriping can be quickly calculated based on the area from the program and the required thickness. This allows precise quantities and eliminates wasted resources.

Through collaboration with the maintenance technicians, asset information (type of light bulb, material, size, power rating, data of install, warranty expiration, paint lines, etc.) can be associated in the program. When a need to repair or replace an asset arises, the technicians don't have to perform field survey to determine materials required; they only need to look in the system. When they make a change or new install they can update the information to ensure the system is current. Proactive asset management and maintenance saves time, manpower, closures and money.

Figure 106 - LIDAR Point Cloud with Edge Lights Identified for Asset Management
(Risner, 2014)

6.9 Laser Scanning for Airfield Pavements

Pavement laser scanning has a more narrow application scope. The majority of work performed by 2D/3D laser systems is for crack detection. Other applications include longitudinal and cross slope determination/modeling, foreign object debris (FOD) and grooving identification. Each will be briefly discussed.

Similar to LIDAR, laser systems capture both range and intensity data. Figure 107 shows this data as well as a combined image. On the left is the range image in which each point has a set of coordinates. The further away from the camera a point is, the darker the point appears. In the center is the intensity image, which this is the strength of the light reflection. As can be seen, the pavement markings appear very strongly against the pavement surface. These images can be combined to form a 3D pavement surface (Laurent, Herbert, Lefebvre, & Savard, 2013).

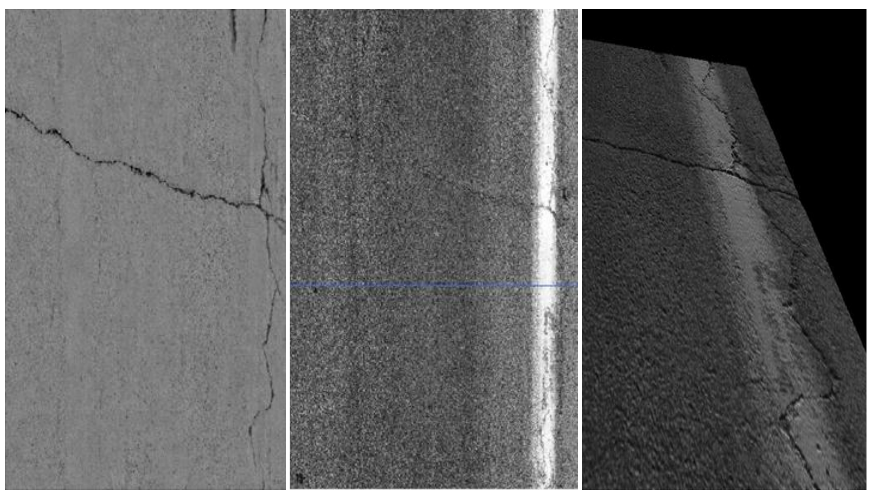


Figure 107 - Laser Scan Data - Range (left), Intensity (center) and 3D Merge (right)
(Laurent, Herbert, Lefebvre, & Savard, 2013)

6.9.1 Condition Survey and Distress Mapping

Similar concepts to LIDAR discussed in Section 6.9.1 apply to laser scanning. The greatest difference is the accuracy and resolution to 1 mm with laser scanning. Figure 108 shows a 2D zoomed in image of a distress from a scan done at Atlanta airport. The grooves and cracking are seen in great detail. A manual or automatic detection survey can be completed at a computer and later mapped via GIS/MicroStation. Based on literature, automated detection for lasers is more common than LIDAR. The output files can also be imported in to MicroPaver (Wang K. C., 2015; Wang, Hou, & Williams, 2011).

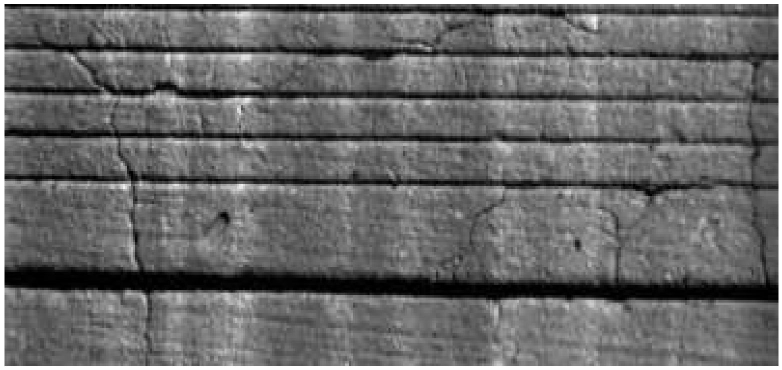


Figure 108 - Laser Scan of Runway 8R at Hartsfield Jackson Atlanta International Airport
(Wang & Hou, 2007)

Figure 109 below, shows a 2D image (grey-scale) and 3D image of cracking and spalling. The 2D image has such a high resolution, it appears as a photo. The green images show the 3D model where the depth of the crack can also be seen. The total length of cracks can be calculated for uses such as: material quantities and labor estimates. Additionally, distresses can be tracked over time to develop growth models for both sections and features of an airfield. Ouyang and Xu, 2013 measured the growth of a pothole distress was approximately 22% over a one year period as seen in Figure 110.

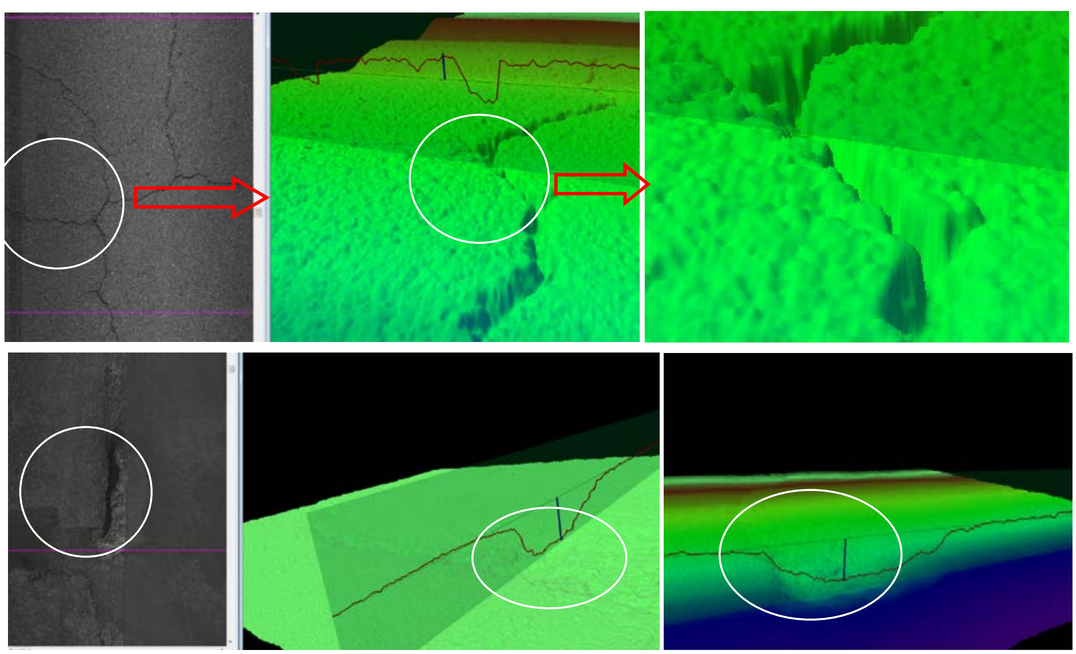


Figure 109 - 2D (grey) and 3D (green) Modeling of Pavement
(Wang, Hou, & Williams, 2011)

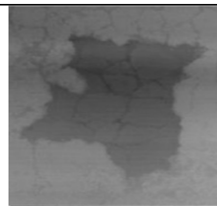
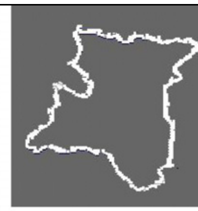
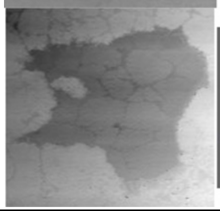
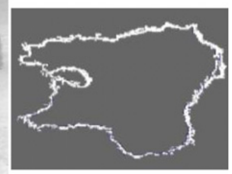
Test date	3D image	Detected pothole	Area (m^2)	Depth (mm)
10/7/2011			0.24	32.4
5/4/2012			0.31	37.9

Figure 110 - Distress Growth Over Time
(Ouyang & Xu, 2013)

6.9.2 Profile Measurements

As discussed previously in Section 6.9.3 there are different types of equipment to collect pavement profiles. Similar to LIDAR, laser profilers provide a continuous full coverage for both cross-slope and longitudinal slope. Figure 111, below shows repeated tests in Salt Lake City, UT using a laser scanner and a conventional ASTM Class 1 profiler. The results coincide with each other. Similar results are seen below in Figure 112 for the slope and cross-slope of roadways in France.

Due to the high resolution of laser scanning, detailed rutting and macro texture can also be measured. Figure 113 shows a transverse profile with the average profile of the surface (red line), variance in texture (blue line), a crack (red circle) and pavement rutting (green circle).

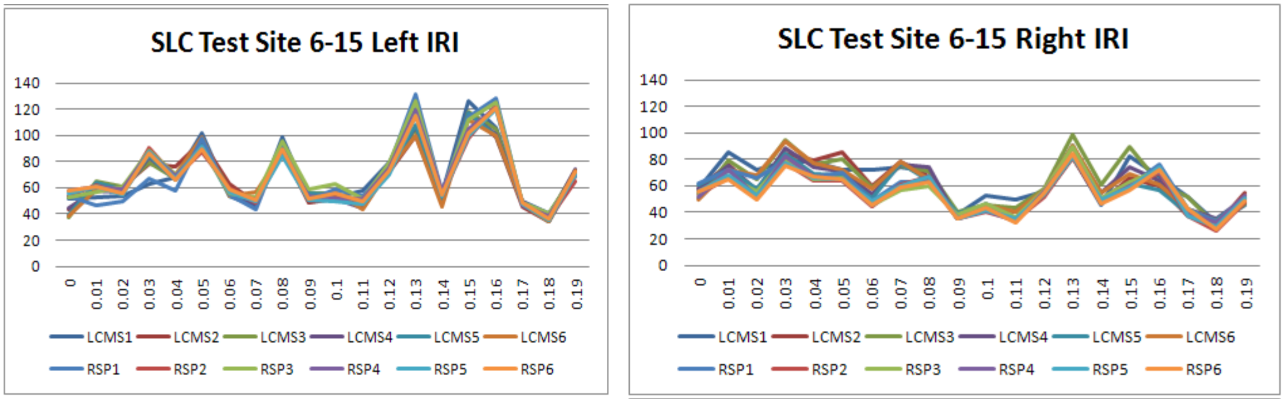


Figure 111 - Longitudinal Profile (IRI) Comparison of Laser Scan (LCMS) vs. Conventional Profiler (RSP)

(Laurent, Herbert, Lefebvre, & Savard, 2013)

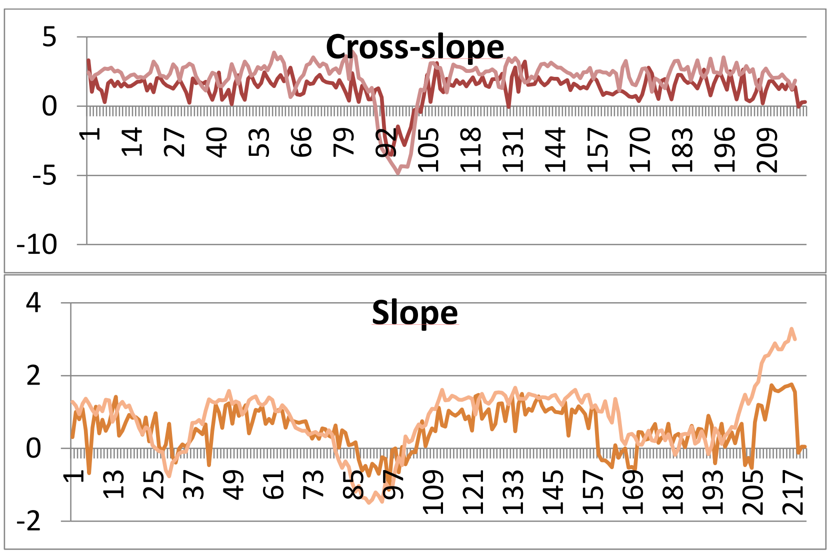


Figure 17. Slope and cross-slope results (degrees vs km) LCMS (bold) Applanix+3 point lasers (non-bold)

Figure 112 - Slope and Cross Slope Comparison (degrees vs. km) of Laser Scan (bold) vs. Conventional Point Scan

(Laurent, Herbert, Lefebvre, & Savard, 2013)

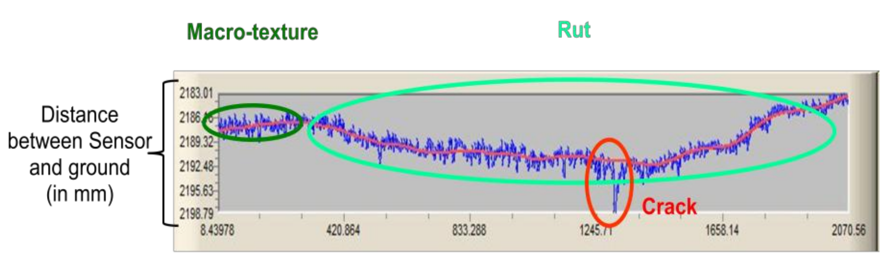


Figure 113 - Laser Scan (2 m section) Showing Asphalt Rutting, Cracking and Texture

(Laurent, Herbert, Lefebvre, & Savard, 2013)

6.9.3 Foreign Object Debris Detection

The safe operation of aircraft is a critical priority. Unsafe operation, whether internally or externally influenced, can cost time, money and loss of life. While operating aircraft on pavement surfaces foreign object debris (FOD) is always a concern. For maintenance personnel FOD removal is a constant battle.

Pavemetrics Systems Inc. has developed a FOD detection system. The user inputs the height and area parameters and drives the vehicle on the pavement. Any object exceeding the parameters is identified. It's exact location and image is recorded as seen below in Figure 114. Based on parameters, the program will also classify the FOD severity as high, medium or low as seen below in Figure 115. In a single pass, the operator can look on the edges of the pavement while the scanners cover most of the aircraft wheel path areas in a single pass when the pavement is busy. At night or during a slow period, a more comprehensive scan with the lasers can be accomplished. This system can assist in rapid assessment and removal of FOD and reduce possible FOD incidents.

Figure 114 - FOD Detected via Laser Scans

Figure 115 - FOD Severity Classification
(Fox & Laurent, 2013)

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APPENDIX

Table 24 - Taxiway A Core Thickness Data

Boring Location	PCC Thickness (in)	Asphalt Thickness (in)	Base (Aggregate) Thickness (in)	Subgrade Description
TWA-1	22	6	7	Sandy Lean Clay
TWA-2	22	2	10	Lean Clay
TWA-3	21	6	7	Lean Clay
TWA-4	21	8	6	Lean Clay with Sand
TWA4-1	22	8	5	Lean Clay with Sand
TWA-5	22	6	7	Lean Clay
TWA5-1	22	5	7	Lean Clay with Sand
TWA-6	24	8	3	Lean Clay with Sand
TWA6-1A	21.25	6.25	0	Lean Clay with Sand
TWA-7	22	6	7	Lean Clay with Sand
TWA7-1	22	6	7	Well graded sand w/gravel
TWA7-2	23.5	0	6.5	Lean Clay with Sand
TWA-8	21	7	7	Lean Clay with Sand
TWA-9	24	5	6	Lean Clay
TWA9-1	20	9	6	Lean Clay with Sand
TWA9-2A	22	9	0	Lean Clay
TWA-10	24	5	6	Lean Clay
TWA10-1	22	6	6	Lean Clay
TWA11-A	21	7	6	Lean Clay with Sand
TWA13-1	22	6	7	Lean Clay
TWA19-1	21.5	0	6	Lean Clay with Sand
TWA20-1A	22.5	0	6	Lean Clay
TWA21-1A	22	0	6	Lean Clay
AVERAGE	**22.03**	**5.27**	**5.85**	

Table 25 - Taxiway B Core Thickness Data

Boring Location	PCC Thickness (in)	Asphalt Thickness (in)	Base (Aggregate) Thickness (in)	Subgrade Description
TWB-1	21.5	6	6	Sandy Lean Clay
TWB-2	20.1	7	6	Sandy Lean Clay
TWB-3	22.5	6	6	Lean Clay with Sand
TWB-4	22	6	6	Lean Clay with Sand
TWB-5A	22	0	20	Lean Clay with Sand
TWB-6	22	6	6	Lean Clay with Sand
TWB-7	22	6	6	Lean Clay
TWB-8A	21.5	5.5	0	Lean Clay with Sand
TWB-9	19.5	4.5	11	Lean Clay
TWB-10A	21.25	5.25	0	Lean Clay
TWB-11	21	6	6	Sandy Lean Clay
TWB-12	21	6	6	Lean Clay with Sand
TWB-13	21.5	6.5	6	Lean Clay with Sand
TWB-15	22.5	5.5	10	Lean Clay with Sand
B1	20.25	5.75	8	
B2	21.25	6	6	
B3	25.5	0	3	
B4	21.5	6.25	6	
B5	23	5.5	12	
B6	22	2.75	6	
B7	22.75	6.25	3	
B8	21.75	5.25	0	
B9	23.25	6	0	
B10	22.75	6	6	
C1	21	6.5	0	
C2	23.5	6.5	0	
C3	22.25	4.75	0	
C4	21.5	5	0	
AVERAGE	**21.88**	**5.31**	**5.18**	

Figure 116 - Longitudinal Cracking at Joint and Patching

Figure 117 - Longitudinal Cracking (PCC) and Fatigue Cracking (Asphalt Inlay)

Figure 118 - Joint Deterioration

Figure 119 - Material Compatibility and Deterioration

Figure 120 - Freeze/Thaw Damage (Pop-outs)

Table 26 - Total Operations Analysis for Groups 1 - 4

Ops >10%

Ops >20%

			% Grps 5-8 Std Dev
			9.93%
		Mean Grps 1-4	Mean Grps 5-8
GROUP 1-4	GROUP 5-8	90.27%	9.73%
Operations	Operations	% Group 1-4	% Group 5-8
4,296	0	100.0%	0%
2,300	1,392	62.3%	38%
2,728	4,601	37.2%	63%
4,873	977	83.3%	17%
7,089	2,002	78.0%	22%
7,954	2,710	74.6%	25%
8,359	109	98.7%	1%
10,643	8,369	56.0%	44%
10,808	0	100.0%	0%
10,943	2,123	83.8%	16%
21,654	85	99.6%	0%
22,586	1,453	94.0%	6%
30,938	6,107	83.5%	16%
31,139	1,971	94.0%	6%
31,247	6,470	82.8%	17%
36,547	7,884	82.3%	18%
38,046	2,323	94.2%	6%
39,257	191	99.5%	0%
50,041	0	100.0%	0%
51,172	1,117	97.9%	2%
51,837	8,147	86.4%	14%
54,545	372	99.3%	1%
55,729	6,296	89.8%	10%
57,510	2,106	96.5%	4%
63,698	0	100.0%	0%
65,890	5,333	92.5%	7%
66,613	6,238	91.4%	9%
74,605	6,661	91.8%	8%
74,632	5,333	93.3%	7%
76,958	2,270	97.1%	3%
79,030	8,750	90.0%	10%
79,553	6,540	92.4%	8%
80,702	3,593	95.7%	4%
95,696	11,313	89.4%	11%
95,949	9,921	90.6%	9%
98,815	8,149	92.4%	8%
100,570	10,865	90.3%	10%
104,525	10,755	90.7%	9%
105,131	9,454	91.7%	8%
105,888	8,198	92.8%	7%
110,964	13,341	89.3%	11%
121,113	9,539	92.7%	7%
122,199	8,283	93.7%	6%
139,581	15,782	89.8%	10%
144,405	12,367	92.1%	8%
150,312	12,254	92.5%	8%
159,952	12,190	92.9%	7%
166,579	16,900	90.8%	9%
168,654	15,591	91.5%	8%
170,075	7,132	96.0%	4%
174,647	16,900	91.2%	9%
178,789	7,132	96.2%	4%
198,583	15,782	92.6%	7%
205,015	15,591	92.9%	7%
209,886	17,353	92.4%	8%
225,307	18,706	92.3%	8%
238,236	27,664	89.6%	10%
239,485	26,368	90.1%	10%
248,215	30,116	89.2%	11%
259,530	30,221	89.6%	10%
262,442	27,641	90.5%	10%
367,900	24,720	93.7%	6%
397,476	26,231	93.8%	6%
403,439	26,034	93.9%	6%
404,643	26,433	93.9%	6%
413,802	24,720	94.4%	6%
432,670	26,034	94.3%	6%

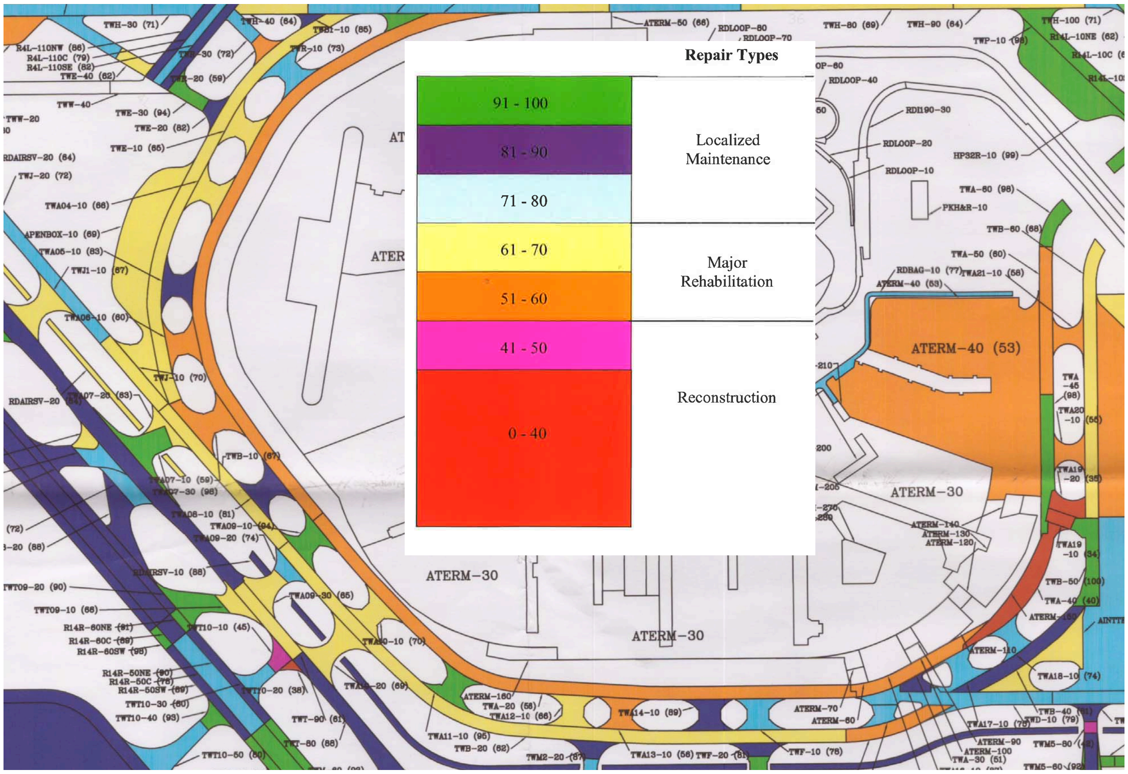

Figure 121 - 2005 PCI Survey for Taxiway A & B

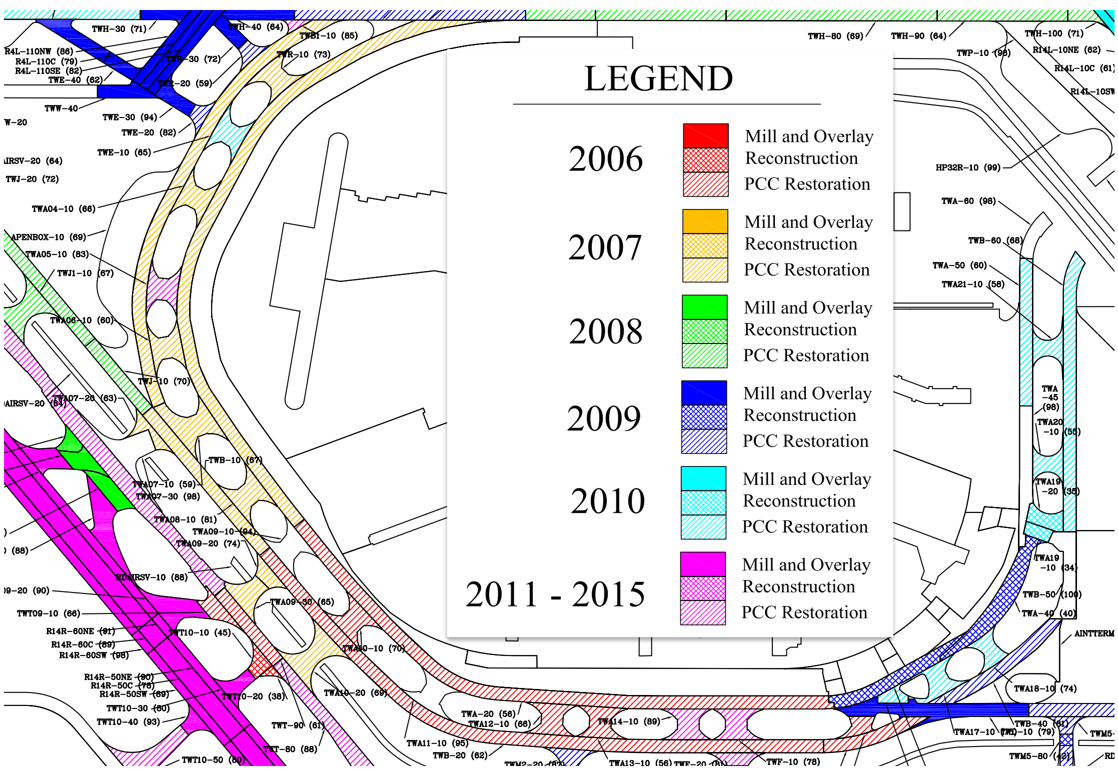

Figure 122 - 2005 - 10 yr Maintenance Plan

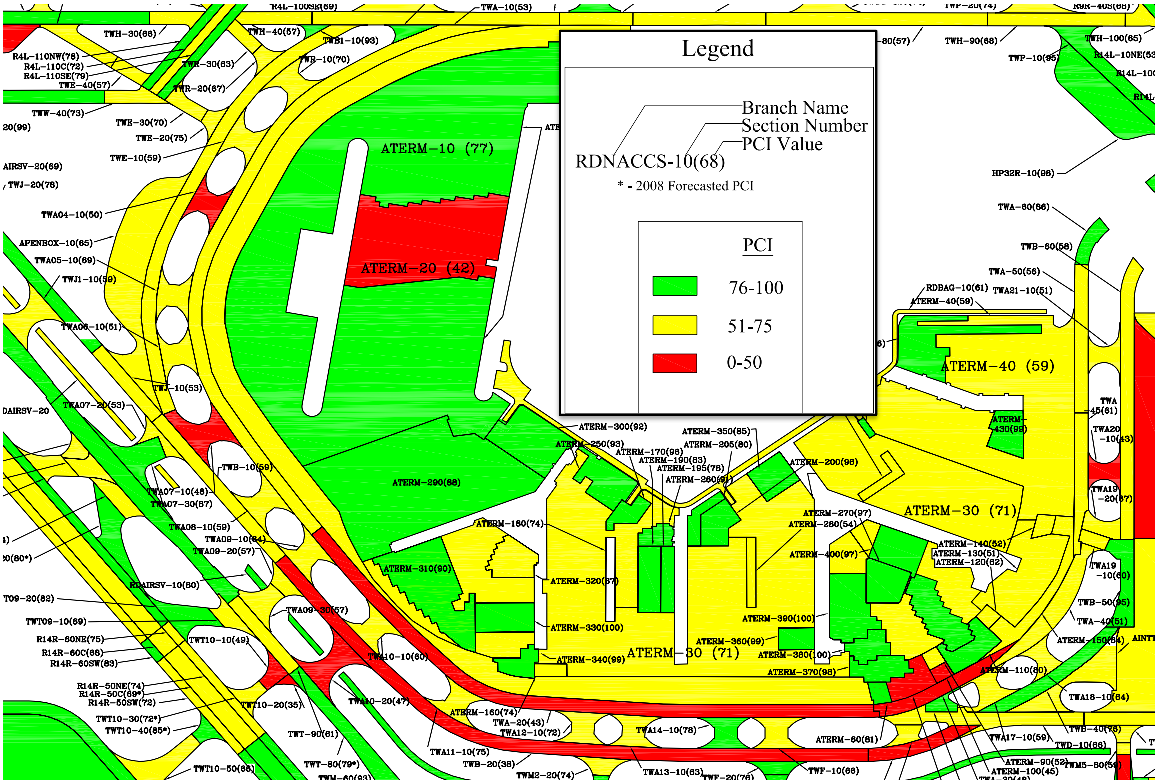

Figure 123 - 2008 PCI Survey for Taxiway A & B

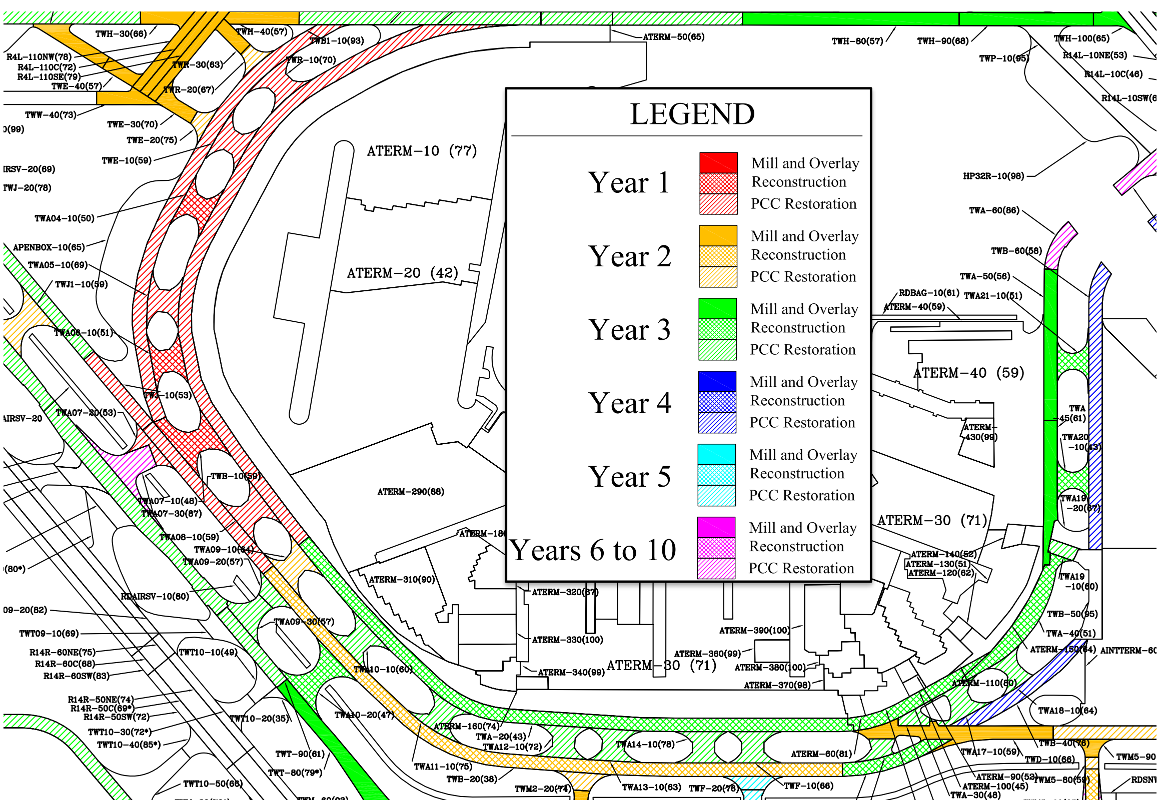

Figure 124 - 2008 - 10 yr Maintenance Plan

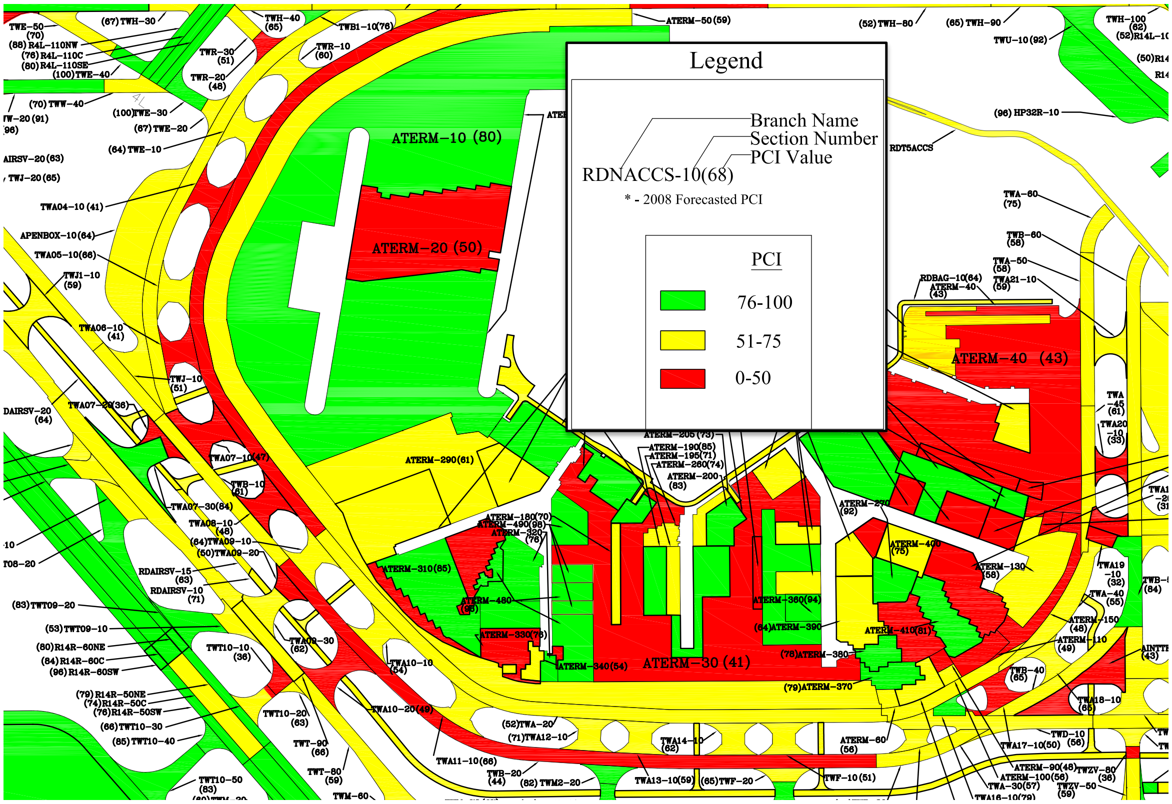

Figure 125 - 2011 PCI Survey for Taxiway A & B

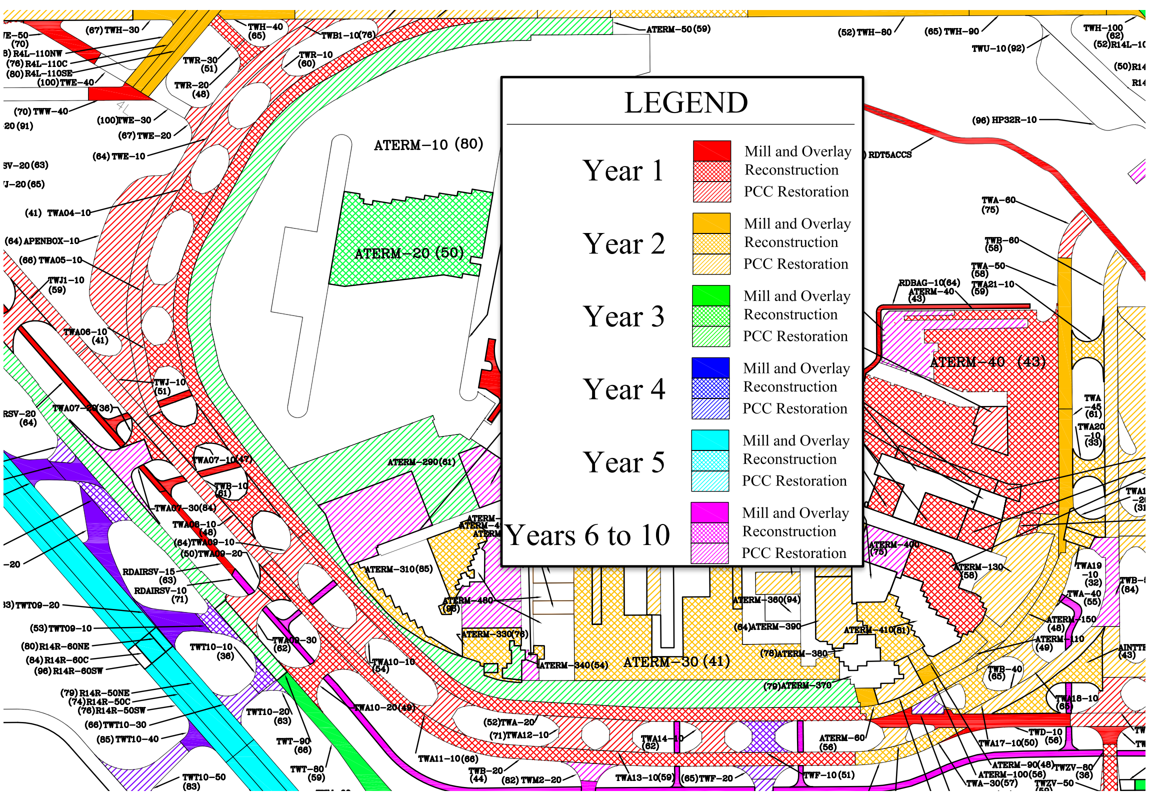

Figure 126 – 2011 - 10 yr Maintenance Plan

Table 27 - Precast Panel Use in Airports in Japan: 1970 - 2014

Year	Owner	Construction location	Scale (m^2)	Construction method
1970	Defense Facilities Administration Agency	Baili airport apron	2,000	Post-tensioning system
1971	Defense Facilities Administration Agency	Baili airport hangar and apron	1,860	Post-tensioning system
1972	Defense Facilities Administration Agency	Baili airport apron	3,170	Post-tensioning system
1973	Hokkaido Regional Development Bureau	Chitose Airport	1,650	Post-tensioning system
1974	Wu Defense Facilities Administration Bureau	Iwakuni second hangar	4,970	Post-tensioning system
1975	Wu Defense Facilities Administration Bureau	Iwakuni third hangar	4,970	Post-tensioning system
1976	Wu Defense Facilities Administration Bureau	Iwakuni surface boat runway	4,100	Precast system
1977	Department of Transportation	Osaka Airport taxiway	540	Precast system
1977	Fukuoka Defense Facilities Administration Bureau	Fortification airport apron	6,500	Post-tensioning system
1980	Fukuoka Defense Facilities Administration Bureau Kumamoto bureau	Nyutabaru apron	6,264	Post-tensioning system
1981	Department of Transportation	Osaka Airport taxiway	3,738	Post-tensioning system
1982	Sapporo Defense Facilities Administration Bureau	Chitose Air Base runway	3,510	Post-tensioning system
1984	Ministry of Transport second Port Construction Bureau	Tokyo airport PC pavement test construction	651	Lift-up method
1984	Ministry of Transport third port construction stations	Osaka Airport taxiway PC version pavement	1,100	Post-tensioning system
1986	Aomori airport construction office	Aomori Airport apron PC pavement	5,736	Post-tensioning system
1986	Sapporo Defense Facilities Administration Bureau	Chitose Airport runway repair pavement	60,000	Precast system
1986	Sapporo Defense Facilities Administration Bureau	Chitose Air Base runway repair pavement temporary version	258	Precast system
1986	Aomori Prefecture	Aomori Airport apron pavement construction (phase I)	5,740	Post-tensioning system
1987	New Tokyo International Airport Authority	Narita PC test pavement	523	Post-tensioning system
1988	Ministry of Transport third port construction stations	Osaka Airport taxiway improvement	2,050	Precast system
1988	Aomori airport construction office	Aomori Airport apron newly established (the second Industrial Zone)	3,375	Post-tensioning system
1988	Ministry of Transport third port construction stations	Osaka Airport taxiway improvement	1,850	Precast system
1988	Ministry of Transport third port construction stations	Osaka Airport taxiway improvement Part 2	600	Precast system

Table 27 (cont.)

1988	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron test pavement	5,550	Precast system
1989	Aomori airport construction office	Aomori Airport apron new	6,300	Post-tensioning system
1989	Ministry of Transport third port construction stations	Osaka Airport taxiway improvement Part 3	1,421	Precast system
1989	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron test paving the 4	3,885	Lift-up method
1989	Aomori Prefecture	Aomori Airport apron pavement construction (III phase)	6,300	Post-tensioning system
1990	Ministry of Transport third port construction stations	Osaka International Airport apron taxiway improvement (Part 4)	2,740	Post-tensioning system
1991	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron pavement Part 1	47,700	Post-tensioning system
1991	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron pavement Part 2	110,051	Post-tensioning system
1991	Ministry of Transport third port construction stations	Osaka International Airport E-4 taxiway improvement	2,450	Precast system
1991	Ministry of Transport third port construction stations	Osaka Airport apron (18th spot), and the like improved	1,700	Precast system
1991	New Tokyo International Airport Authority	New Tokyo International Airport taxiway new construction	14,840	Post-tensioning system
1992	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron pavement Part 3	6,488	Post-tensioning system
1992	New Tokyo International Airport Authority	New Tokyo International Airport C3 runway and taxiway pavement	12,904	Post-tensioning system
1992	New Tokyo International Airport Authority	New Tokyo International Airport by taxi-way contact taxiway PC pavement	9,311	Post-tensioning system
1992	Kansai International Airport Co., Ltd.	Kansai International Airport apron PC pavement (Part 1)	193,120	Post-tensioning system
1992	Kansai International Airport Co., Ltd.	Kansai International Airport apron PC pavement (Part 2)	188,810	Post-tensioning system
1992	Kansai International Airport Co., Ltd.	Kansai International Airport apron PC pavement (Part 3)	36,430	Post-tensioning system
1992	Ministry of Transport third port construction stations	Osaka Airport apron (18th spot), and the like improved	1,600	Precast system

Table 27 (cont.)

1992	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement	1,008	Precast system
1992	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement (Part 3)	1,378	Precast system
1992	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement work (stage I)	2,905	Precast system
1992	Ministry of Transport second Port Construction Bureau	Tokyo International Airport contact taxiway new construction	9,815	Post-tensioning system
1993	Ministry of Transport fourth port construction stations	Kagoshima airport apron PC version pavement	3,200	Precast system
1993	Ministry of Transport third port construction stations	Osaka International Airport W-2 taxiway improvement	1,000	Precast system
1993	Kansai International Airport Co., Ltd.	Kansai International Airport apron pavement lift up test	6,700	Post-tensioning system
1993	Ministry of Transport third port construction stations	Osaka International Airport apron (18th spot) improvement work (Part 3)	1,450	Precast system
1993	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway pavement Part 1	2,228	Precast system
1993	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway pavement Part 3	2,158	Precast system
1993	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway pavement that 4	1,944	Precast system
1993	Ministry of Transport second Port Construction Bureau	Haneda Airport lift up test		Lift-up method
1993	All Nippon Airways Co., Ltd.	All Nippon Airways Kansai International Airport cargo export shed floor PC pavement	2,929	Post-tensioning system
1993	Osaka police headquarters	Osaka prefectural police Kansai International Airport hangar PC pavement version	409	Precast system
1993	All Nippon Airways Co., Ltd.	ANA Kanku machine supplies warehouse PC pavement	588	Post-tensioning system
1993	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway pavement Part 5	1,517	Precast system
1993	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron pavement construction	307, 311	Post-tensioning system

Table 27 (cont.)

1993	Kansai International Airport Co., Ltd.	Kansai International Airport apron pavement construction	420,000	Post-tensioning system
1993	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement work (II phase)	2,275	Precast system
1994	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron pavement (Part 9)	48,399	Post-tensioning system
1994	Kansai International Airport Co., Ltd.	Kansai Airport lift up construction	14,793	Lift-up method
1994	All Nippon Airways Co., Ltd.	ANA Kansai International Airport vehicle maintenance field PC version pavement	551	Post-tensioning system
1994	All Nippon Airways Co., Ltd.	All Nippon Airways Kansai International Airport cargo export warehouse repair	80	Lift-up method
1994	Ministry of Transport third port construction stations	Osaka International Airport apron 17th spot	1,200	Precast system
1994	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway pavement	1,656	Precast system
1994	Ministry of Transport fourth port construction stations	Kagoshima airport apron pavement	3,328	Precast system
1994	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron pavement	45,295	Lift-up method
1995	Ministry of Transport second Port Construction Bureau	Haneda Airport apron pavement	23,637	Post-tensioning system
1995	Unwa-sho second Port Construction Bureau	Haneda Airport apron pavement such as construction Part 12	23,637	Lift-up method
1995	Ministry of Transport second Port Construction Bureau	Haneda Airport taxiway outside pavement and improvements such as construction	49,266	Post-tensioning system lift up system
1995	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement work	1,640	Precast system
1995	Ministry of Transport fourth port construction stations	Miyazaki airport apron improvement work	2,202	Precast system
1995	Ministry of Transport fourth port construction stations	Kagoshima airport apron improvement work	1,700	Precast system
1995	Ministry of Transport fourth port construction stations	Kagoshima airport apron improvement work (second order)	860	Precast system

Table 27 (cont.)

1995	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement work (III phase)	2,520	Precast system
1996	Yokohama Defense Facilities Administration Bureau	Atsugi (7) runway pavement PC version construction	22,118	Precast system
1996	Ministry of Transport second Port Construction Bureau	Tokyo International Airport taxiway outside pavement construction	1,902	Lift-up system
1996	Department of Transportation Civil Aviation Bureau Osaka	Osaka International Airport apron PC version repair work	Fifty	Precast system
1996	Ministry of Transport third port construction stations	Osaka International Airport W-2 taxiway improvement work	3,450	Precast system
1996	Kansai International Airport Co., Ltd.	Kansai International Airport apron (north) pavement construction	39,280	Lift-up system
1996	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron pavement	4,186	Precast system
1996	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport taxiway repair work	35	Post-tensioning system
1996	Hiroshima Defense Facilities Administration Bureau	Iwakuni hangar PC version pavement construction	4,853	Lift-up method
1996	Ministry of Transport fourth port construction stations	Oita Airport apron pavement	1,459	Precast system
1996	Ministry of Transport fourth port construction stations	Kagoshima airport apron pavement	1,266	Precast system
1996	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement work (stage IV)	2,100	Precast system
1996	Ministry of Transport fourth port construction stations	Oita airport apron	714	Precast system
1997	New Tokyo International Airport Authority	Narita A-1 taxiway pavement	298	Precast system
1997	Ministry of Transport third port construction stations	Osaka Airport apron taxiway version pavement	1,350	Precast system
1997	Ministry of Transport third port construction stations	Osaka Airport apron taxiway version repair	1,200	Precast system
1997	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron pavement	3,811	Precast system
1997	Ministry of Transport first port construction stations	Komatsu Airport apron improvement work	134	Precast system
1997	Ministry of Transport first port construction stations	Komatsu Airport apron improvement work	232	Precast system

Table 27 (cont.)

1997	Ministry of Transport fourth port construction stations	Kagoshima Airport PC version pavement construction	1,700	Precast system
1997	Ministry of Transport first port construction stations	Komatsu Airport apron taxiway renovation (Part 1)	4,050	Precast system
1998	Ministry of Transport second Port Construction Bureau	Tokyo International Airport taxiway pavement improvement work	6,313	Lift-up system
1998	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron improvement work	3,900	Lift-up system
1998	Ministry of Transport first port construction stations	Komatsu Airport apron improvement work	4,204	Precast system
1998	Kansai International Airport Co., Ltd.	Kansai airport apron (south) pavement construction	38,000	Post-tensioning system
1998	Ministry of Transport third port construction stations	Osaka International Airport apron taxiway pavement	2,700	Precast system
1998	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement work	3,971	Precast system
1998	Ministry of Transport fifth Port Construction Bureau	Nagoya Airport apron taxiway improvement work	2,689	Precast system
1998	Ministry of Transport second Port Construction Bureau	Sendai Airport apron taxiway improvement work	4,350	Precast system
1998	Aomori civil engineering office	Aomori Airport apron pavement construction	6,441	Post-tensioning system
1998	Fukushima airport construction office	Fukushima Airport PC version	1,123	Precast system
1998	Ministry of Transport first port construction stations	Komatsu Airport apron improvement work	7,298	Precast system
1998	Kansai International Airport Co., Ltd.	Kansai International Airport apron (south) pavement construction	38,340	Post-tensioning system
1998	Kansai International Airport ⑭	Kansai International Airport apron (north) pavement construction	36,160	Post-tensioning system
1998	Ministry of Transport second Port Construction Bureau	Sendai Airport apron taxiway renovation	2,220	Precast system
1998	New Tokyo International Airport Authority	New Tokyo International Airport taxiway new construction	5,481	Precast system
1999	Ministry of Transport first port construction stations	Komatsu Airport apron improvement work that made 3	375	Precast system

Table 27 (cont.)

1999	Hokkaido Regional Development Bureau Hakodate Development and Construction Department	Hakodate Airport apron pavement construction	3,997	Precast system
1999	Kansai International Airport Co., Ltd.	Kansai airport apron taxiway improvement work	4,690	Lift-up system
1999	Ministry of Transport second Port Construction Bureau	Sendai Airport PPC version laying	875	Precast system
1999	New Tokyo International Airport Authority	New Tokyo International Airport taxiway new construction (Part 2)	1,886	Precast system
1999	Kansai International Airport Co., Ltd.	Kansai International Airport apron (south) pavement construction	36,160	Post-tensioning system
2000	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron pavement (Part 2)	29,000	Post-tensioning system
2000	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron pavement (Part 1)	37,000	Post-tensioning system
2000	Ministry of Transport second Port Construction Bureau	Tokyo International Airport apron improvement work	18,000	Lift-up system
2000	Ministry of Transport first port construction stations	Komatsu Airport apron improvement work	1,153	Precast system
2000	Ministry of Transport third port construction stations	Osaka Airport apron improvement work (Part 8)	3,150	Precast system
2000	Ministry of Transport fourth port construction stations	Fukuoka Airport taxiway improvement work (second order)	753	Precast system
2000	Ministry of Transport first port construction stations	Komatsu Airport apron taxiway renovation (Part 2)	4,450	Precast system
2001	Diplomatic relations Ministry Kanto Regional Development Bureau	Tokyo International Airport apron pavement (Part 4)	20,000	Post-tensioning system
2001	New Tokyo International Airport Authority	Narita PC buffered version Construction	1,050	Post-tensioning system
2001	Ministry Kinki Regional Development Bureau	Osaka International Airport apron taxiway pavement construction	2,111	Precast system
2001	Ministry Kinki Regional Development Bureau	Osaka International Airport apron improvement work (Part 10)	1,950	Precast system
2001	Ministry Kyushu Regional Development Bureau	Fukuoka Airport taxiway improvement work	2,883	Precast system
2001	Ministry Kyushu Regional Development Bureau	Fukuoka Airport taxiway improvement work (second order)	3,767	Precast system

Table 27 (cont.)

2002	Diplomatic relations Ministry Kanto Regional Development Bureau	Tokyo International Airport apron pavement (Part 6)	31,300	Post-tensioning system
2002	Ministry Kinki Regional Development Bureau	Osaka International Airport apron improvement work (Part 12)	4,167	Precast system
2002	Ministry Kyushu Regional Development Bureau	Fukuoka Airport taxiway improvement work	848	Precast system
2002	Ministry of Land, Infrastructure and Transport Kyushu Regional Development Bureau	Fukuoka Airport taxiway improvement work (4th)	4,617	Precast system
2002	Ministry of Land, Infrastructure and Transport Kyushu Regional Development Bureau	Fukuoka Airport taxiway improvement work	3,212	Precast system
2003	Diplomatic relations Ministry Kanto Regional Development Bureau	Haneda west apron lift up construction		Lift-up method
2003	Diplomatic relations Ministry Kanto Regional Development Bureau	Haneda Airport east apron its 7 Construction	19,000	Post-tensioning system
2004	San-Ai Oil Co., Ltd., ANA other	Haneda Airport east apron refueling tube change work	1,107	Post-tensioning system
2004	Ministry of Land, Infrastructure and Transport Kinki Regional Development Bureau	Osaka International Airport apron improvement work	2,807	Precast system
2004	Kansai International Airport Co., Ltd.	Kanku lift up L7 construction		Lift-up method
2005	Ministry of Land, Infrastructure and Transport Kinki Regional Development Bureau	Osaka International Airport apron improvement work	3,800	Precast system
2006	Ministry of Land, Infrastructure and Transport Kyushu Regional Development Bureau	Fukuoka Airport apron improvement work (second order)	3,222	Precast system
2006	Ministry of Land, Infrastructure and Transport Kyushu Regional Development Bureau	Fukuoka Airport apron improvement work (third order)	3,576	Precast system
2006	Ministry Kinki Regional Development Bureau	Osaka Airport apron taxiway improvement work	2225	Precast system
2006	Kansai International Airport Co., Ltd.	2006 fiscal PC pavement lift up construction	1674	Lift-up method
2006	Diplomatic relations MinistryKanto Regional Development Bureau	Tokyo International Airport East Passenger Terminal district Engineering taxiway out improvement work	5600	Lift-up method
2006	Diplomatic relations MinistryKanto Regional Development Bureau	Tokyo International Airport west passenger terminal area apron improvement work	28600	Lift-up method

Table 27 (cont.)

2007	Ministry Kinki Regional Development Bureau	2007 Osaka International Airport apron taxiway improvement work	2949	Precast system
2007	Cabinet Office Okinawa General office	Naha Airport taxiway improvement work	9819	Precast system
2007	Ministry Kyushu Development Bureau	Fukuoka Airport taxiway improvement work	4807	Precast system
2007	Ministry Kyushu Development Bureau	Fukuoka Airport apron improvement work (third order)	3600	Precast system
2007	Ministry Kyushu Development Bureau	Fukuoka Airport apron improvement work (4th)	2464	Precast system
2007	Ministry Kyushu Development Bureau	Fukuoka Airport apron (No.53) improvement work	586.4	Precast system (single version)
2008	Kansai International Airport facility engineer (Ltd.)	# 8, # 34, # 105 spot PC pavement version stepped adjustment		Lift-up method
2008	Ministry Hokkaido Regional Development Bureau	Hakodate Airport PC version production	2625	Precast system (single version)
2009	Cabinet Office Okinawa General Bureau	Naha Airport PC pavement construction (A-0)	7799	Precast system (large edition method)
2009	Cabinet Office Okinawa General Bureau	Naha Airport PC pavement construction (E-1)	2250	Precast system (large edition method)
2009	Cabinet Office Okinawa General Bureau	Naha Airport PC pavement construction (A-2)	5303	Precast system (large edition method)
2009	Ministry Kyushu Development Bureau	Fukuoka Airport PC pavement construction (A2)	4311	Precast system (large edition method)
2009	Ministry Hokkaido Regional Development Bureau	Hakodate Airport apron construction (6 Industrial District)	4167	Precast system (single version)
2010	Ministry Hokkaido Regional Development Bureau	Hakodate Airport apron construction (5 Industrial Zone)	4200	Precast system (single version)
2011	Ministry of Land, Infrastructure and Transport Kanto Regional Development Bureau	Haneda Airport 1, 17 th SPOT apron improvement work	400	Precast system
2011	Kansai International Airport Co., Ltd.	Kansai International Airport (V-1) lift-up construction		Lift-up method
2011	Cabinet Office Okinawa General Bureau	Naha Airport PC pavement construction (A-3)	2247	Precast system (large edition method)
2011	Ministry Hokkaido Regional Development Bureau	Hakodate Airport apron construction (4 Industrial Zone)	4700	Precast system (single version)
2012	Ministry of Defense South Kanto Defense Bureau	Atsugi runway PPC version manufacture and installation	8,220	Precast system (large edition method)

Table 27 (cont.)

2012	Ministry of Land, Infrastructure and Transport Kanto Regional Development Bureau	Haneda 2SPOT repair work	352	Precast system (single version)
2012	Cabinet Office Okinawa General Bureau Development and Construction Department	Naha Airport PC pavement construction (A-4)	3,676	Precast system (large edition method)
2013	New Kansai International Airport Co., Ltd.	Kansai International Airport (L7) grouting construction		lift up
2013	Cabinet Office Okinawa General Bureau Development and Construction Department	Naha Airport PC pavement construction (A-4) (Part 2)	5,150	Precast system (large edition method)
2013	Cabinet Office Okinawa General Bureau Development and Construction Department	Naha Airport PC pavement construction (A-5)	4,520	Precast system (large edition method)
2014	Cabinet Office Okinawa General Bureau Development and Construction Department	Naha Airport PC pavement construction (A-5, A-6)	12,492	Precast system (large edition method)
2014	Ministry of Defense South Kanto Defense Bureau	Atsugi (25 e) runway maintenance paving work	1,829	Precast system (large edition method)

Table 28 - CMR Equipment Productivity and Fuel Efficiency

Equipment	Productivity (ft^2/hr)	Productivity (tn/hr)	Fuel Efficiency (gal/hr)
Dozer CAT D6T - 207 hp		226.20	4.65
Dozer CAT D7E - 238 hp		282.75	5.70
Dozer CAT D8T - 317 hp		471.25	7.26
Dozer CAT D9T - 436 hp		754.00	9.26
User Input			
Wheel Loader CAT 972M XE - 299 hp		764.00	7.09
Wheel Loader CAT 980M - 386 hp (13 tn)		1182.00	8.80
Wheel Loader CAT 986H - 409 hp		1249.00	9.00
User Input			
Motor Grader CAT 140M2 - 200 hp (14 ft width)		350.00	4.86
Motor Grader CAT 160M3 - 221 hp (14 ft width)		375.00	5.12
User Input			
Excavator, track CAT 320E L - 153 hp		177.81	3.60
Excavator, track CAT 335FL CR - 200 hp		274.93	4.50
Excavator, track CAT 336F - 303 hp		357.00	7.19
User Input			
Dump Truck - 325 hp (10 cy)		685.13	8.21
Dump Truck CAT CT660 - 365-475 hp (15 cy)		1027.69	9.53
User Input			
Snow Equip Blade 22ft - 400 hp	2244000.00		9.40
Snow Equip Rollover Plow - 350 hp	2244000.00		8.75
Snow Equip Broom 22 ft - 500 hp	2244000.00		13.60
SnowPlow Dump Truck - 425 hp	1188000.00		12.80
User Input			
Soil Compactor (tamping) CAT 825H - 354 hp (11 ft width)		805.00	7.23
Soil Compactor (tamping) CAT 825K - 405 hp (11 ft width)		886.00	8.69
Vibratory Compactor (steel drum) CAT CB44B - 102 hp (5 ft width)		1711.00	2.90
Vibratory Compactor (steel drum) CAT CB54 XW - 137 hp (6.6 ft width)		1832.00	3.45
Vibratory Soil Compactor (tamping) CAT CP54B - 131 hp (7 ft width)		700.00	3.40
Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)		736.00	3.90
User Input			
Pneumatic Roller CAT CW34 - 133 hp (82 in)		700.00	3.40
Pneumatic Roller CAT PS150C HW - 100 hp (68 in)		648.00	2.90
User Input			
AC Paver CAT AS3301C - (26ft pave width, vibratory screed)		1600.00	11.93
AC Paver CAT AS4252C - (26ft pave width, tamper screed)		1752.00	11.93
User Input			
Pavement Reclaimer CAT RM300 - 350 hp (2.7 mph, 96 in wide)		900.00	19.40
Pavement Reclaimer CAT RM500B - 546 hp (2mph, 96 in wide)			24.20
Pavement Reclaimer (CIP) Wirtgen 2200 SM - 950 hp (2mph, 96 in wide)		1200.00	41.21
User Input			
Concrete Mixer Truck CAT CT681 - 365-430 hp		54.68	8.20
User Input			
Millng Machine (cold planer) CAT PM200 - 575 hp (width 79 in)		550.00	19.50
Millng Machine (cold planer) Wirtgen W1900/60 - 400 hp (width 60 in)		300.00	21.50
Millng Machine (cold planer) Wirtgen W1900/75 - 400 hp (width 75 in)		400.00	21.50
Millng Machine (cold planer) Wirtgen W2200/75 - 875 hp (width 75 in)		1100.00	41.00
User Input			
PCC Breaker MHB Badger Breaker - 350 hp - 14-18 inPCC		889.00	7.50
PCC Breaker MHB Badger Breaker - 350 hp - 18-24 inPCC		1167.00	7.50
PCC Breaker MHB Badger Breaker - 350 hp -		500.00	7.50
PCC Breaker MHB Badger Breaker - 350 hp - 14-18 inPCC		889.00	7.50
PCC Breaker MHB Badger Breaker - 350 hp - 18-24 inPCC		1167.00	7.50
PCC Breaker MHB Badger Breaker - 350 hp - 8-10 inPCC		500.00	7.50
PCC Crack-Seat T8600 Badger Breaker - 8-10 in PCC		1500.00	5.00
PCC Pre-Break T8600 Badger Breaker - 14-18 in PCC		667.00	5.00
PCC Pre-Break T8600 Badger Breaker - 18-24 in PCC		570.00	5.00
PCC Resonance Breaker Resinant Machines RB-700 - 550 hp		590.70	62.50
User Input - Hydraulic Hammer		357.00	7.19
Asphalt Reclaimer Wirtger HM4500 - 325 hp		215.00	12.68
User Input			
Cranes (HP=100)		40.00	2.18
Cranes (HP=175)		50.00	3.23
Cranes (HP=300)		71.67	5.28
User Input			
Slipform Paver - 208 hp (28' x 18" max depth)		1134.00	8.10
Slipform Paver - 275 - 300 hp (40' x 18" max depth)		2880.00	11.00
Slipform Paver - 420 hp (52' x 17.7" max depth)		3125.00	21.16
User Input			
Texture Concrete Curing Machine Wirtger TCM1800 - 100 hp	26300.00		3.00
Texture Concrete Curing Machine Wirtger TCM950 - 55 hp	21200.00		2.75
Concrete Saw (length*1/2" width) (Diesel) - 100 hp	15.63		2.79
Concrete Saw (length*1/2" width) (Diesel) - 175 hp	31.25		3.73
Concrete Saw (length*1/2" width) (Diesel) - 300 hp	46.88		7.45
Tamper Diesel Hand - 6 hp	600.00		0.10
Compactor - Plate (Diesel) - 11 hp	1050.00		0.21
Compactor - Plate (Diesel) - 25 hp	2000.00		0.50
Diesel Skid Steer Loaders (HP=75)		123.50	0.82
Diesel Skid Steer Loaders (HP=100)		164.67	1.20
Diesel Skid Steer Loaders (HP=175)		247.00	1.48
User Input			
Groover - HEM Magnacut - 175 hp	2250.00		15.60
Groover Asphalt - Cardinal Safe-T -(600 - 700 hp)	9000.00		19.00
Groover PCC - Cardinal Safe-T - (600 - 700 hp)	6300.00		17.00
User Input			
Emulsion Aplicator (Prime, Tack and Seal) - 175 hp	356400.00		4.24
User Input			
Rubber Remover Cyclone 4600 - 375 hp	5700.00		11.10
Rubber Remover Trackjet - 400 hp (full-size version)	2125.00		4.10
Rubber Remover Trackjet - 200 hp (small version)	2125.00		4.10
Rubber Remover SH8000R	9425.00		25.40
User Input			
Diamond Grinder PC 6000 - 680 hp	7560.00		23.00
Diamond Grinder PRM 3804 - 400-600 hp	6000.00		20.00
User Input			
Crack Sealer (asphalt) Crafco - 41 hp		0.45	2.50
Asphalt Patch Repair - 20 hp		0.43	1.17
Joint Sealer - 20 hp		0.43	1.00
User Input			
HIR Recycler - 800 hp		1713.00	39.63
User Input			
Paint Striper	468.75		25.40
Tractor Trailer - Tank (5000 gal/hr of slurry, binder, etc.) - 500 hp		45000.00	13.63
Broom Truck Smow	2244000.00	1.00	15.00
Crane for Precast (150 ton)	273900.00		8.00

Table 29 - Taxiway A and B's Construction Activities and Fuel Consumption for AC

ASPHALT CONSTRUCTION								
Construction Activity	**Equipment**	**Brand/Model**	**Quantity (tons or sf)**	**Productivity (tn/hr or sq ft/hr)**	**Hours of Operation**	**Fuel Consumption (gal/hr)**	**Fuel Type**	**Fuel Consumed (gal)**
Land Clearing and Removal	Bulldozer	Dozer CAT D9T - 436 hp	182,952	754.00	242.64	9.26	Diesel	2,247
	Wheel Loader	Wheel Loader CAT 986H - 409 hp	182,952	1249.00	146.48	9.00	Diesel	1,318
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (15 cy)	182,952	1027.69	178.02	9.53	Diesel	1,697
Excavation (Edge Drains)	Excavator	Excavator, track CAT 320E L - 153 hp	0	177.81	0.00	3.60	Diesel	-
Grading	Grader	Motor Grader CAT 160M3 - 221 hp (14 ft width)	0	375.00	0.00	5.12	Diesel	-
Earthwork	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)	0	1182.00	0.00	8.80	Diesel	-
	Excavator	Excavator, track CAT 320E L - 153 hp	0	177.81	0.00	3.60	Diesel	-
Soil Stabilization	Soil Mixer	Tractor Trailer - Tank (5000 gal/hr of slurry, binder, etc.) - 500 hp	0	45000.00	0.00	13.63	Diesel	-
	Grader	Motor Grader CAT 140M2 - 200 hp (14 ft width)	0	350.00	0.00	4.86	Diesel	-
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	0	736.00	0.00	3.9	Diesel	-
Crushed Aggregate Base	Wheel Loader (Agg)	Wheel Loader CAT 986H - 409 hp	62,093	1249.00	49.71	9.00	Diesel	447
	Grader (Agg)	Motor Grader CAT 160M3 - 221 hp (14 ft width)	46,570	375.00	124.19	5.12	Diesel	636
	Bulldozer (Agg)	Dozer CAT D9T - 436 hp	108,662	754.00	144.11	9.26	Diesel	1,335
	Dump Truck (Agg)	Dump Truck CAT CT660 - 365-475 hp (15 cy)	155,232	1027.69	151.05	9.53	Diesel	1,440
	Compaction (Agg)	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	155,232	736.00	210.91	3.9	Diesel	823
Asphalt Paving	Paver	AC Paver CAT AS3301C - (26ft pave width, vibratory screed)	120,582	1600.00	75.36	11.93	Diesel	899
	Tack Coat	Emulsion Aplicator (Prime, Tack and Seal) - 175 hp	6,652,800	356400.00	18.67	4.24	Diesel	79
	Prime Coat	Emulsion Aplicator (Prime, Tack and Seal) - 175 hp	2,772,000	356400.00	7.78	4.24	Diesel	33
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	120,582	700.00	172.26	3.40	Diesel	586
Pavement Marking	Striping Machine	Paint Striper	6,653	468.75	14.19	25.40	Diesel	360
							Total Gal=	**11,899**

Table 30 - Taxiway A and B's Construction Activities and Fuel Consumption for PCC

PORTLAND CEMENT CONCRETE CONSTRUCTION								
Construction Activity	Equipment	Brand/Model	Quantity (tons or sf)	Productivity (tn/hr or sq ft/hr)	Hours of Operation	Fuel Consumption (gal/hr)	Fuel Type	Fuel Consumed (gal)
Land Clearing and Removal	Bulldozer	Dozer CAT D9T - 436 hp	224,532	754	298	9	Diesel	2,758
	Wheel Loader	Wheel Loader CAT 986H - 409 hp	224,532	1249	180	9	Diesel	1,618
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	224,532	685	328	8	Diesel	2,691
Excavation (Edge Drains)	Excavator	Excavator, track CAT 320E L - 153 hp		178	0	4	Diesel	-
Grading	Grader	Motor Grader CAT 160M3 - 221 hp (14 ft width)	36867.60	375	98	5	Diesel	503
Earthwork	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)		1182	0	9	Diesel	-
	Excavator	Excavator, track CAT 320E L - 153 hp		178	0	4	Diesel	-
Soil Stabilization	Soil Mixer	Tractor Trailer - Tank (5000 gal/hr of slurry, binder, etc.) - 500 hp	0.00	45000	0	14	Diesel	-
	Grader	Motor Grader CAT 160M3 - 221 hp (14 ft width)	0.00	375	0	5	Diesel	-
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	0.00	736	0	4	Diesel	-
Crushed Aggregate Base	Wheel Loader	Wheel Loader CAT 986H - 409 hp	23,285	1249	19	9	Diesel	168
	Grader	Motor Grader CAT 160M3 - 221 hp (14 ft width)	17,464	375	47	5	Diesel	238
	Bulldozer	Dozer CAT D9T - 436 hp	40,748	754	54	9	Diesel	500
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (15 cy)	58,212	1028	57	10	Diesel	540
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	58,212	736	79	4	Diesel	308
Concrete Paving	Slipform Paver	Slipform Paver Wirtger SP16000 - 420 hp (52' x 17.7" max depth)	218,295	3125	70	21	Diesel	1,478
	Texture Curing Machine	Texture Concrete Curing Machine Wirtger TCM1800 - 100 hp	1,663,200	26300	63	3	Diesel	190
Joints	Joint Sealer	Joint Sealer - 20 hp	18.14	0	43	1	Diesel	43
	Sawcutter	Concrete Saw (length*1/2" width) (Diesel) - 100 hp	6,468	16	414	3	Diesel	1,155
Pavement Marking	Striping Machine	Paint Striper	66,528	469	142	25	Diesel	3,605
							Total Gal=	15,794

Table 31 – Rubblization – Mill/Inlay Case Maintenance/Rehabilitation Activities - AC

ASPHALT MAINTENANCE							
Pavement Design Life	50						
Main Activity	Occurrences in Design Life	Single Occurrence Area (ft^2)	Design Life Occurrence Area (ft^2)	Depth (in)	Design Life Occurrence Vol (ft^3)	Density (lbs/ft^3)	Weight (tn)
Seal Cracks	4	1,417	5669	0.75	354.3	68.5	12.1
Asphalt Patch	2	60,440	120880	5	50366.7	145	3651.6
Asphalt Mill	1	589,122	589122.2	1	49093.5	145	3559.3
Asphalt Overlay			0		0.0		0.0
Asphalt Inlay	1	762,733	762733.3	1	762733.3	145	55298.2
Cold In-Place Recycling			0		0.0		0.0
Hot In-Place Recycling			0		0.0		0.0
Full Depth Reclamation			0		0.0		0.0
Concrete Overlay			0		0.0		0.0
Rubber Removal			0				
Diamond Grind Surface			0				
Surface Treatment			0				
Restriping	5	6,653	33264	0.015	41.6	92.57	1.9
Touchdown Grooving			0				
Snow Removal		1,108,800	0				
Saw Cut (patch perimeter*1/2" width)	4	2518.333333	10073.3				
Tack Coat	1	620,880	620880	0.375	19402.5	68.5	664.5
Brooming	9125	1,108,800	10117800000				

Table 32 – Rubblization – Mill/Inlay Case Maintenance/Rehabilitation Activities - PCC

PORTLAND CEMENT CONCRETE MAINTENANCE								
Pavement Design Life	**50**							
Main Activity	**Occurrences in Design Life**	**Single Occurrence Area (ft^2)**	**Design Life Occurrence Area (ft^2)**	**Depth (in)**	**Design Life Occurrence Vol (ft^3)**	**Density (lbs/ft^3)**	**Weight (tn)**	
Seal Cracks (bitumen)	4	511	2046	1	128	69	4	
Joint Seal	4	6155.5	24622.0	0.8	1538.9	89.8	69.1	
Concrete Demolition	2	4489.6	8979.2	31.0	23196.3	150.0	1739.7	
Rubblization	1	250000.0	250000.0	21.0	437500.0	150.0	32812.5	
Partial Depth Repair	2	3076.4	6152.8	10.0	5127.3	150.0	384.6	
Full Depth Repair	2	1413.2	2826.4	21.0	4946.2	150.0	371.0	
PCC Mill	1	250000.0	250000.0	5.0	104166.7	150.0	7812.5	
Asphalt Patch					0.0		0.0	
Asphalt Inlay			0.0		0.0		0.0	
Asphalt Overlay			0.0		0.0		0.0	
Concrete Overlay			0.0		0.0		0.0	
Rubber Removal			0.0					
Diamond Grind Surface			0.0					
Surface Treatment			0.0					
Restriping	4	66528.0	266112.0	0.0	332.6	92.6	15.4	
Touchdown Grooving			0.0					
Snow Removal		1663200.0	0.0					
Saw Cut (total repair perimeter*1/2" width)	4	499.6	1998.3					
Brooming	9125	1663200.0	15176700000.0					
Tack Coat	1	0.0	0.0	0.1	0.0	68.5	0.0	

Table 33 - Precast Case Maintenance and Rehabilitation Activities - AC

ASPHALT MAINTENANCE							
Pavement Design Life	**50**						
Main Activity	**Occurrences in Design Life**	**Single Occurrence Area (ft^2)**	**Design Life Occurrence Area (ft^2)**	**Depth (in)**	**Design Life Occurrence Vol (ft^3)**	**Density (lbs/ft^3)**	**Weight (tn)**
Seal Cracks	4	1,386	5544	0.75	346.5	68.5	11.9
Asphalt Patch	2	55,440	110880	5	46200.0	145.0	3349.5
Asphalt Mill	3	1,108,800	3326400	2	554400.0	145.0	40194.0
Asphalt Overlay			0		0.0		0.0
Asphalt Inlay	3	1,108,800	3326400	2	554400.0	145.0	40194.0
Cold In-Place Recycling			0		0.0		0.0
Hot In-Place Recycling			0		0.0		0.0
Full Depth Reclamation			0		0.0		0.0
Concrete Overlay			0		0.0		0.0
Rubber Removal			0				
Diamond Grind Surface			0				
Surface Treatment			0				
Restriping	5	6,653	33264	0.015	41.6	92.6	1.9
Touchdown Grooving			0				
Snow Removal		1,108,800	0				
Saw Cut (patch perimeter*1/2" width)	4	2310	9240				
Tack Coat	1	3,437,280	3437280	0.375	107415.0	68.5	3679.0
Brooming	9125	1,108,800	10117800000				

Table 34 – Precast Case – Maintenance/Rehabilitation Activities - PCC

PORTLAND CEMENT CONCRETE MAINTENANCE								
Pavement Design Life	50							
Main Activity	Occurrences in Design Life	Single Occurrence Area (ft^2)	Design Life Occurrence Area (ft^2)	Depth (in)	Design Life Occurrence Vol (ft^3)	Density (lbs/ft^3)	Weight (tn)
Seal Cracks (bitumen)	4	542.6	2170.5	0.75	135.7	68.5	4.6
Joint Seal	4	6468.0	25872.0	0.75	1617.0	89.77	72.6
Concrete Demolition	2	4489.6	8979.2	31	23196.3	150	1739.7
Rubblization			0.0		0.0		0.0
Partial Depth Repair	2	3076.4	6152.8	10	5127.3	150	384.6
Full Depth Repair	2	1413.2	2826.4	21	4946.2	150	371.0
PCC Mill			0.0		0.0		0.0
Asphalt Patch					0.0		0.0
Asphalt Inlay			0.0		0.0		0.0
Asphalt Overlay			0.0		0.0		0.0
Concrete Overlay			0.0		0.0		0.0
Rubber Removal			0.0				
Diamond Grind Surface	1	250000.0	250000.0	0.125			
Surface Treatment			0.0				
Restriping	4	66528.0	266112.0	0.015	332.6	92.57	15.4
Touchdown Grooving			0.0				
Snow Removal		1663200.0	0.0				
Saw Cut (total repair perimeter*1/2" width)	4	812.1	3248.3				
Brooming	9125	1663200.0	15176700000.0				
Precast Panel Installation	1	250000.0	250000.0	21	437500.0	150	32812.5
Precast Panel Flowable Fill (Underslab)	1	249375.0	249375.0	1.5	31171.9	118.49	1846.8
Precast Panel Flowable Fill (Dowel Slots)	1	28000.0	28000.0	4	9333.3	118.49	553.0
Precast Panel Concrete Demolition	1	250000.0	250000.0	21	437500.0	150	32812.5
Tack Coat	1	250000.0	250000.0	0.125	2604.2	68.5	89.2

Table 35 – Reconstruction Case Maintenance and Rehabilitation Activities - AC

ASPHALT MAINTENANCE							
Pavement Design Life	50						
Main Activity	Occurrences in Design Life	Single Occurrence Area (ft^2)	Design Life Occurrence Area (ft^2)	Depth (in)	Design Life Occurrence Vol (ft^3)	Density (lbs/ft^3)	Weight (tn)
Seal Cracks	4	1,386	5544	0.75	346.50	68.5	11.87
Asphalt Patch	2	55,440	110880	5	46200.00	145	3349.50
Asphalt Mill	3	1,108,800	3326400	2	554400.00	145	40194.00
Asphalt Overlay			0		0.00		0.00
Asphalt Inlay	3	1,108,800	3326400	2	554400.00	145	40194.00
Cold In-Place Recycling			0		0.00		0.00
Hot In-Place Recycling			0		0.00		0.00
Full Depth Reclamation			0		0.00		0.00
Concrete Overlay			0		0.00		0.00
Rubber Removal			0				
Diamond Grind Surface			0				
Surface Treatment			0				
Restriping	5	6,653	33264	0.015	41.58	92.57	1.92
Touchdown Grooving			0				
Snow Removal			0				
Saw Cut (patch perimeter*1/2" width)	4	2310	9240				
Tack Coat	1	3,437,280	3437280	0.375	107415.00	68.5	3678.96
Brooming	1	250,000	250000	0.375	7812.50	68.5	267.58
Asphalt Demolition	9125	1,108,800	10117800000				
Asphalt Reconstruction	1	3,000,000	3000000	1	250000.00	145	18125.00

Table 36 – Reconstruction Case Maintenance and Rehabilitation Activities - PCC

PORTLAND CEMENT CONCRETE MAINTENANCE							
Pavement Design Life	50						
Main Activity	Occurrences in Design Life	Single Occurrence Area (ft^2)	Design Life Occurrence Area (ft^2)	Depth (in)	Design Life Occurrence Vol (ft^3)	Density (lbs/ft^3)	Weight (tn)
Seal Cracks (bitumen)	4	542.63	2170.533333	0.75	135.66	68.5	4.65
Joint Seal	4	6,468.00	25872	0.75	1617.00	89.77	72.58
Concrete Demolition	2	4,490	8979.2	31	23196.27	150	1739.72
Rubblization			0		0.00		0.00
Partial Depth Repair	2	3,076	6152.8	10	5127.33	150	384.55
Full Depth Repair	2	1413.2	2826.4	21	4946.20	150	370.97
PCC Mill			0		0.00		0.00
Asphalt Patch					0.00		0.00
Asphalt Inlay			0		0.00		0.00
Asphalt Overlay			0		0.00		0.00
Concrete Overlay			0		0.00		0.00
Rubber Removal			0				
Diamond Grind Surface			0				
Surface Treatment			0				
Restriping	4	66,528	266112	0.015	332.64	92.57	15.40
Touchdown Grooving			0				
Snow Removal		1,663,200	0				
Saw Cut (total repair perimeter*1/2" width)	4	440.68	1762.733333				
Brooming	9125	1,663,200	15176700000				
Concrete Demolition - Reconstruction	1	250,000	250000	21	437500.00	150	32812.50
Joint Sealant - Reconstruction							3.51

Table 37 - Rubblization and Mill/Inlay Case PCC CMR Values

PORTLAND CEMENT CONCRETE MAINTENANCE							
Maintenance Activity	**Equipment**	**Brand/Model**	**Quantity (tons or sf)**	**Productivity (tn/hr or sq ft/hr)**	**Hours of Operation**	**Fuel Consumption (gal/hr)**	**Fuel Consumed (gal)**
Rubblization	Multi Head Breaker	PCC Breaker MHB Badger Breaker - 350 hp - 8-10 in PCC	32813	500	66	8	492
	Guillotine Style Breaker	PCC Pre-Break T8600 Badger Breaker - 18-24 in PCC	32813	570	58	5	288
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	32813	736	45	4	174
Concrete Demolition	Hydraulic Hammer/Breaker	User Input - Hydraulic Hammer	1740	893	2	7	14
	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)	1740	1182	1	9	13
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	9552	685	14	8	114
Milling	Milling Machine	Milling Machine (cold planer) Wirtgen W2200/75 - 875 hp (width 75 in)	7813	1100	7	41	291
Rubber Removal	Rubber Remover	Rubber Remover Cyclone 4600 - 375 hp	0	5700	0	11	-
Asphalt Patching	Sawcutter	Concrete Saw (length*1/2" width) (Diesel) - 100 hp	1998	16	128	3	357
	Dump Truck (Cold Asphalt)	Dump Truck CAT CT660 - 365-475 hp (10 cy)	0	685	0	8	-
	Patch Repair	Asphalt Patch Repair - 20 hp	0	0	0	1	-
	Hand Compaction	Tamper Diesel Hand - 6 hp	0	2000	0	1	-
Asphalt Overlay/Inlay	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	0	685	0	8	-
	Paver	AC Paver CAT AS4252C - (26ft pave width, tamper screed)	0	1752	0	12	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB54 XW - 137 hp (6.6 ft width)	0	1832	0	3	-
Concrete Overlay	Slipform Paver	Slipform Paver Wirtger SP16000 - 420 hp (52' x 17.7" max depth)	0	3125	0	21	-
	Texture Curing Machine	Texture Concrete Curing Machine Wirtger TCM1800 - 55 hp	0	26300	0	3	-
Rout and Seal Cracks	Crack Sealer	Crack Sealer (asphalt) Crafco - 41 hp	4	0	10	3	25
Full Depth Repair (PCC)	Concrete Mixer	Concrete Mixer Truck CAT CT681 - 365-430 hp	371	55	7	8	56
Partial Depth Repair (PCC)	Concrete Mixer	Concrete Mixer Truck CAT CT681 - 365-430 hp	385	55	7	8	58
Pavement Removal	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)		1182	0	9	-
Diamond Grind Surface	Diamond Grinder	Diamond Grinder PC 6000 - 680 hp	0	7560	0	23	-
Joint Sealing	Joint Sealer	Joint Sealer - 20 hp	69	0	162	1	162
Surface Treatment	Emulsion Applicator	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	0	356400	0	4	-
Grooving	Groover	Groover Asphalt - Cardinal Safe-T -(600 - 700 hp)	0	9000	0	19	-
Restriping	Striping Machine	Paint Striper	276112	469	568	25	14,962
Snow Removal	Snow Removal Equipment	Snow Equip Blade 22ft - 400 hp		2244000	0	9	-
Other Equipment	Brooming Large	Broom Truck Snow	15176700000	2244000	6763	10	67,632
						Total Gal=	**84,637**

Table 38 - Rubblization and Mill/Inlay Case AC CMR Values

ASPHALT MAINTENANCE - from Rubbliz Inlay and Shoulders							
Maintenance Activity	Equipment	Brand/Model	Quantity (tons or sf)	Productivity (tn/hr or sq ft/hr)	Hours of Operation	Fuel Consumption (gal/hr)	Fuel Consumed (gal)
Milling	Milling Machine	Milling Machine (cold planer) Wirtgen W2200/75 - 875 hp (width 75 in)	3559	1100	3	41	133
Cold In-Place Recycling	CIR Recycler	Asphalt Reclaimer Wirtger HM4500 - 325 hp	0	215	0	13	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB44B - 102 hp (5 ft width)	0	1711	0	3	-
Hot In-Place Recycling	HIR Recycler	HIR Recycler - 800 hr	0	1713	0	40	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB44B - 102 hp (5 ft width)	0	1711	0	3	-
Rubber Removal	Rubber Remover	Rubber Remover Cyclone 4600 - 375 hp	0	5700	0	11	-
Asphalt Patching	Sawcutter	Concrete Saw (length*1/2" width) (Diesel) - 100 hp	10073	16	645	3	1,798
	Dump Truck (Cold Asphalt)	Dump Truck CAT CT660 - 365-475 hp (10 cy)	3652	685	5	8	44
	Patch Repair	Asphalt Patch Repair - 20 hp	3652	0	8562	1	10,017
	Hand Compaction	Tamper Diesel Hand - 6 hp	3652	2000	2	1	0.91
Asphalt Overlay/Inlay	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	55298	685	81	8	663
	Paver	AC Paver CAT AS4252C - (26ft pave width, tamper screed)	55298	1752	32	12	377
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	55298	700	79	3	269
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB54 XW - 137 hp (6.6 ft width)	55298	736	75	3.9	293
Tack Coat	Tack Coat	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	620880	356400	2	4	7
Concrete Overlay	Slipform Paver	Slipform Paver Wirtger SP16000 - 420 hp (52' x 17.7" max depth)	0	3125	0	21	-
	Texture Curing Machine	Texture Concrete Curing Machine Wirtger TCM1800 - 55 hp	0	26300	0	3	-
Pavement Removal	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)	0	1182	0	9	-
Diamond Grind Surface	Diamond Grinder	Diamond Grinder PC 6000 - 680 hp	0	7560	0	23	-
Crack Sealing	Crack Sealer	Crack Sealer (asphalt) Crafco - 41 hp	5669	0	12699	3	31,746
Full Depth Reclamation	Pavement Reclaimer	Pavement Reclaimer CAT RM300 - 350 hp (2.7 mph, 96 in wide)	0	1200	0	41	-
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	0	736	0	4	-
Surface Treatment	Emulsion Applicator	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	0	356400	0	4	-
Grooving	Groover	Groover Asphalt - Cardinal Safe-T -(600 - 700 hp)	0	9000	0	19	-
Restriping	Striping Machine	Paint Striper	33264	469	71	25	1,802
Snow Removal	Snow Removal Equipment	Snow Equip Blade 22ft - 400 hp	0	2244000	0	9	-
Other Equipment	Brooming Large	Broom Truck Snow	10117800000	2244000	4509	10	45,088
	Broom Small	Other Equipment Defined by User		0	0	0	-
	Additional Equipment	Other Equipment Defined by User		0	0	0	-
	Additional Equipment	Other Equipment Defined by User		0	0	0	-
	Additional Equipment	Other Equipment Defined by User		0	0	0	-
						Total Gal=	92,238

Table 39 - Precast Panel Case PCC CMR Values

PORTLAND CEMENT CONCRETE MAINTENANCE							
Maintenance Activity	**Equipment**	**Brand/Model**	**Quantity (tons or sf)**	**Productivity (tn/hr or sq ft/hr)**	**Hours of Operation**	**Fuel Consumption (gal/hr)**	**Fuel Consumed (gal)**
Rubblization	Multi Head Breaker	PCC Breaker MHB Badger Breaker - 350 hp - 8-10 in PCC	0	500	0	8	-
	Guillotine Style Breaker	PCC Pre-Break T8600 Badger Breaker - 18-24 in PCC	0	570	0	5	-
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	0	736	0	4	-
Concrete Demolition	Breaker/Hydraulic Hammer	User Input - Hydraulic Hammer	1740	893	2	7	14
	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)	1740	1182	1	9	13
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	34552	685	50	8	414
Milling	Milling Machine	Milling Machine (cold planer) Wirtgen W2200/75 - 875 hp (width 75 in)	0	1100	0	41	-
Rubber Removal	Rubber Remover	Rubber Remover Cyclone 4600 - 375 hp	0	5700	0	11	-
Asphalt Patching	Sawcutter	Concrete Saw (length*1/2" width) (Diesel) - 100 hp	3248	16	208	3	580
	Dump Truck (Cold Asphalt)	Dump Truck CAT CT660 - 365-475 hp (10 cy)	0	685	0	8	-
	Patch Repair	Asphalt Patch Repair - 20 hp	0	0	0	1	-
	Hand Compaction	Tamper Diesel Hand - 6 hp	0	2000	0	1	-
Asphalt Overlay/Inlay	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	0	685	0	8	-
	Paver	AC Paver CAT AS4252C - (26ft pave width, tamper screed)	0	1752	0	12	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB54 XW - 137 hp (6.6 ft width)	0	0	0	0	-
Concrete Overlay	Slipform Paver	Slipform Paver Wirtger SP16000 - 420 hp (52' x 17.7" max depth)	0	3125	0	21	-
	Texture Curing Machine	Texture Concrete Curing Machine Wirtger TCM1800 - 55 hp	0	26300	0	3	-
Rout and Seal Cracks	Crack Sealer	Crack Sealer (asphalt) Crafco - 41 hp	5	0	10	3	26
Full Depth Repair (PCC)	Concrete Mixer	Concrete Mixer Truck CAT CT681 - 365-430 hp	371	55	7	8	56
Partial Depth Repair (PCC)	Concrete Mixer	Concrete Mixer Truck CAT CT681 - 365-430 hp	385	55	7	8	58
Pavement Removal	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)		1182	0	9	-
Diamond Grind Surface	Diamond Grinder	Diamond Grinder PC 6000 - 680 hp	250000	7560	33	23	761
Joint Sealing	Joint Sealer	Joint Sealer - 20 hp	73	0	170	1	170
Surface Treatment	Emulsion Applicator	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	0	356400	0	4	-
Grooving	Groover	Groover Asphalt - Cardinal Safe-T -(600 - 700 hp)	0	9000	0	19	-
Restriping	Striping Machine	Paint Striper	266112	469	568	25	14,420
Snow Removal	Snow Removal Equipment	Snow Equip Blade 22ft - 400 hp		2244000	0	9	-
Brooming	Brooming Large	Broom Truck Snow	15176700000	2244000	6763	10	67,632
Precast Panel Install	Precast Crane	Crane for Precast (150 ton)	65625	142	461	6	2,858
	Excavator w/Hydraulic Hammer	User Input		893	0	0	-
	Volumetric Mixer	Volumetric Mixer/Pump (CT660 - 475hp)	2400	290	8	10	79
	Additional Equipment	Other Equipment Defined by User		0	0	7	-
						Total Gal=	**87,080**

Table 40 - Precast Panel Case AC CMR Values

ASPHALT MAINTENANCE							
Maintenance Activity	**Equipment**	**Brand/Model**	**Quantity (tons or sf)**	**Productivity (tn/hr or sq ft/hr)**	**Hours of Operation**	**Fuel Consumption (gal/hr)**	**Fuel Consumed (gal)**
Milling	Milling Machine	Milling Machine (cold planer) Wirtgen W2200/75 - 875 hp (width 75 in)	40194	1100	37	41	1,498
Cold In-Place Recycling	CIR Recycler	Asphalt Reclaimer Wirtger HM4500 - 325 hp	0	215	0	13	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB44B - 102 hp (5 ft width)	0	1711	0	3	-
Hot In-Place Recycling	HIR Recycler	HIR Recycler - 800 hr	0	1713	0	40	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB44B - 102 hp (5 ft width)	0	1711	0	3	-
Rubber Removal	Rubber Remover	Rubber Remover Cyclone 4600 - 375 hp	0	5700	0	11	-
Asphalt Patching	Sawcutter	Concrete Saw (length*1/2" width) (Diesel) - 100 hp	9240	16	591	3	1,649
	Dump Truck (Cold Asphalt)	Dump Truck CAT CT660 - 365-475 hp (10 cy)	3350	685	5	8	40
	Patch Repair	Asphalt Patch Repair - 20 hp	3350	0	7853	1	9,189
	Hand Compaction	Tamper Diesel Hand - 6 hp	3350	2000	2	1	1
Asphalt Overlay/Inlay	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	40194	685	59	8	482
	Paver	AC Paver CAT AS4252C - (26ft pave width, tamper screed)	40194	1752	23	12	274
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	40194	700	57	3	195
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB54 XW - 137 hp (6.6 ft width)	40194	736	55	4	213
Tack Coat	Tack Coat	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	3437280	356400	10	4	41
Concrete Overlay	Slipform Paver	Slipform Paver Wirtger SP16000 - 420 hp (52' x 17.7" max depth)	0	3125	0	21	-
	Texture Curing Machine	Texture Concrete Curing Machine Wirtger TCM1800 - 55 hp	0	26300	0	3	-
Pavement Removal	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)	0	1182	0	9	-
Diamond Grind Surface	Diamond Grinder	Diamond Grinder PC 6000 - 680 hp	0	7560	0	23	-
Crack Sealing	Crack Sealer	Crack Sealer (asphalt) Crafco - 41 hp	5544	0	12419	3	31,046
Full Depth Reclamation	Pavement Reclaimer	Pavement Reclaimer CAT RM300 - 350 hp (2.7 mph, 96 in wide)	0	1200	0	41	-
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	0	736	0	4	-
Surface Treatment	Emulsion Applicator	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	0	356400	0	4	-
Grooving	Groover	Groover Asphalt - Cardinal Safe-T -(600 - 700 hp)	0	9000	0	19	-
Restriping	Striping Machine	Paint Striper	33264	469	71	25	1,802
Snow Removal	Snow Removal Equipment	Snow Equip Blade 22ft - 400 hp	0	2244000	0	9	-
Other Equipment	Brooming Large	Broom Truck Snow	10117800000	2244000	4509	10	45,088
	Broom Small	Other Equipment Defined by User		0	0	0	-
	Additional Equipment	Other Equipment Defined by User		0	0	0	-
	Additional Equipment	Other Equipment Defined by User		0	0	0	-
	Additional Equipment	Other Equipment Defined by User		0	0	0	-
						Total Gal=	**91,519**

Table 41 - Reconstruction Case PCC CMR Values

PORTLAND CEMENT CONCRETE MAINTENANCE							
Maintenance Activity	Equipment	Brand/Model	Quantity (tons or sf)	Productivity (tn/hr or sq ft/hr)	Hours of Operation	Fuel Consumption (gal/hr)	Fuel Consumed (gal)
Rubblization	Multi Head Breaker	PCC Breaker MHB Badger Breaker - 350 hp - 8-10 in PCC	0	500	0	8	-
	Guillotine Style Breaker	PCC Pre-Break T8600 Badger Breaker - 18-24 in PCC	0	570	0	5	-
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	0	736	0	4	-
Concrete Demolition	Breaker/Hydraulic Hammer	User Input - Hydraulic Hammer	1740	893	2	7	14
	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)	1740	1182	1	9	13
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	1740	685	3	8	21
Milling	Milling Machine	Milling Machine (cold planer) Wirtgen W2200/75 - 875 hp (width 75 in)	0	1100	0	41	-
Rubber Removal	Rubber Remover	Rubber Remover Cyclone 4600 - 375 hp	0	5700	0	11	-
Asphalt Patching	Sawcutter	Concrete Saw (length*1/2" width) (Diesel) - 100 hp	1763	16	113	3	315
	Dump Truck (Cold Asphalt)	Dump Truck CAT CT660 - 365-475 hp (10 cy)	0	685	0	8	-
	Patch Repair	Asphalt Patch Repair - 20 hp	0	0	0	1	-
	Hand Compaction	Tamper Diesel Hand - 6 hp	0	2000	0	1	-
Asphalt Overlay/Inlay	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	0	685	0	8	-
	Paver	AC Paver CAT AS4252C - (26ft pave width, tamper screed)	0	1752	0	12	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB54 XW - 137 hp (6.6 ft width)	0	0	0	0	-
Concrete Overlay	Slipform Paver	Slipform Paver Wirtger SP16000 - 420 hp (52' x 17.7" max depth)	0	3125	0	21	-
	Texture Curing Machine	Texture Concrete Curing Machine Wirtger TCM1800 - 55 hp	0	26300	0	3	-
Rout and Seal Cracks	Crack Sealer	Crack Sealer (asphalt) Crafco - 41 hp	5	0	10	3	26
Full Depth Repair (PCC)	Concrete Mixer	Concrete Mixer Truck CAT CT681 - 365-430 hp	371	55	7	8	56
Partial Depth Repair (PCC)	Concrete Mixer	Concrete Mixer Truck CAT CT681 - 365-430 hp	385	55	7	8	58
Pavement Removal	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)		1182	0	9	-
Diamond Grind Surface	Diamond Grinder	Diamond Grinder PC 6000 - 680 hp	0	7560	0	23	-
Joint Sealing	Joint Sealer	Joint Sealer - 20 hp	73	0	170	1	170
Surface Treatment	Emulsion Applicator	Emulsion Aplicator (Prime, Tack and Seal) - 175 hp	0	356400	0	4	-
Grooving	Groover	Groover Asphalt - Cardinal Safe-T -(600 - 700 hp)	0	9000	0	19	-
Restriping	Striping Machine	Paint Striper	266112	469	568	25	14,420
Snow Removal	Snow Removal Equipment	Snow Equip Blade 22ft - 400 hp		2244000	0	9	-
Other Equipment	Brooming Large	Broom Truck Snow	15176700000	2244000	6763	10	67,632
Concrete Demolition - Recon	Breaker/Hydraulic Hammer	User Input - Hydraulic Hammer	32813	893	37	7	264
	Excavator	Excavator, track CAT 336F - 303 hp	32813	357	92	7	661
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (15 cy)	32813	0	0	8	-
Crushed Agg Base - Recon	Wheel Loader	Wheel Loader CAT 986H - 409 hp	3500	1249	3	9	25
	Grader	Motor Grader CAT 160M3 - 221 hp (14 ft width)	2625	375	7	5	36
	Bulldozer	Dozer CAT D9T - 436 hp	6125	754	8	9	75
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (15 cy)	8750	1028	9	10	81

Table 41 - (cont.)

	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	8750	736	12	4	46
Concrete Paving - Recon	Slipform Paver	Slipform Paver Wirtger SP16000 - 420 hp (52' x 17.7" max depth)	32813	3125	11	21	222
	Texture Curing Machine	Texture Concrete Curing Machine Wirtger TCM1800 - 100 hp	250000	26300	10	3	29
Joints - Recon	Joint Sealer	Joint Sealer - 20 hp	4	0	8	1	8
	Sawcutter	Concrete Saw (length*1/2" width) (Diesel) - 100 hp	1251	16	80	3	223
Grading-Post Demolition	Grader	User Input		0	0	0	-
						Total Gal=	**84,395**

Table 42 - Reconstruction Case AC CMR Values Figure

ASPHALT MAINTENANCE								
Maintenance Activity	**Equipment**	**Brand/Model**	**Quantity (tons or sf)**	**Productivity (tn/hr or sq ft/hr)**	**Hours of Operation**	**Fuel Consumption (gal/hr)**	**Fuel Type**	**Fuel Consumed (gal)**
Milling	Milling Machine	Millng Machine (cold planer) Wirtgen W2200/75 - 875 hp (width 75 in)	40194	1100	37	41	Diesel	1,498
Cold In-Place Recycling	CIR Recycler	Asphalt Reclaimer Wirtger HM4500 - 325 hp	0	215	0	13	Diesel	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	Diesel	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB44B - 102 hp (5 ft width)	0	1711	0	3	Diesel	-
Hot In-Place Recycling	HIR Recycler	HIR Recycler - 800 hr	0	1713	0	40	Diesel	-
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	0	700	0	3	Diesel	-
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB44B - 102 hp (5 ft width)	0	1711	0	3	Diesel	-
Rubber Removal	Rubber Remover	Rubber Remover Cyclone 4600 - 375 hp	0	5700	0	11	Diesel	-
Asphalt Patching	Sawcutter	Concrete Saw (length*1/2" width) (Diesel) - 100 hp	9240	16	591	3	Diesel	1,649
	Dump Truck (Cold Asphalt)	Dump Truck CAT CT660 - 365-475 hp (10 cy)	3350	685	5	8	Diesel	40
	Patch Repair	Asphalt Patch Repair - 20 hp	3350	0	7853	1	Diesel	9,189
	Hand Compaction	Tamper Diesel Hand - 6 hp	3350	2000	2	1	Diesel	1
Asphalt Overlay/Inlay	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (10 cy)	40194	685	59	8	Diesel	482
	Paver	AC Paver CAT AS4252C - (26ft pave width, tamper screed)	40194	1752	23	12	Diesel	274
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	40194	700	57	3	Diesel	195
	Vibratory Steel Drum Compactor	Vibratory Compactor (steel drum) CAT CB54 XW - 137 hp (6.6 ft width)	40194	736	55	3.8	Diesel	213
Tack Coat	Tack Coat	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	3437280	356400	10	4	Diesel	41
Concrete Overlay	Slipform Paver	Slipform Paver Wirtger SP16000 - 420 hp (52' x 17.7" max depth)	0	3125	0	21	Diesel	-
	Texture Curing Machine	Texture Concrete Curing Machine Wirtger TCM1800 - 55 hp	0	26300	0	3	Diesel	-
Pavement Removal	Wheel Loader	Wheel Loader CAT 980M - 386 hp (13 tn)	0	1182	0	9	Diesel	-
Diamond Grind Surface	Diamond Grinder	Diamond Grinder PC 6000 - 680 hp	0	7560	0	23	Diesel	-
Crack Sealing	Crack Sealer	Crack Sealer (asphalt) Crafco - 41 hp	5544	0	12419	3	Diesel	31,046
Full Depth Reclamation	Pavement Reclaimer	Pavement Reclaimer CAT RM300 - 350 hp (2.7 mph, 96 in wide)	0	1200	0	41	Diesel	-
	Compaction	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	0	736	0	4	Diesel	-
Surface Treatment	Emulsion Applicator	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	0	356400	0	4	Diesel	-
Grooving	Groover	Groover Asphalt - Cardinal Safe-T -(600 - 700 hp)	0	9000	0	19	Diesel	-
Restriping	Striping Machine	Paint Striper	33264	469	71	25	Diesel	1,802
Snow Removal	Snow Removal Equipment	Snow Equip Blade 22ft - 400 hp	0	2244000	0	9	Diesel	-
Brooming	Brooming Large	Broom Truck Snow	10117800000	2244000	4509	10	Diesel	45,088
Asphalt Demolition	Excavator	Excavator, track CAT 336F - 303 hp	18125	357	51	7	Diesel	365
	Dump Truck	Dump Truck CAT CT660 - 365-475 hp (15 cy)	18125	1028	18	10	Diesel	168
Grading-Post Demolition	Grader	Motor Grader CAT 160M3 - 221 hp (14 ft width)	83160	375	222	5	Diesel	1,135
Crushed Agg Base - Post Demolition	Wheel Loader (Agg)	Wheel Loader CAT 986H - 409 hp	0	1249	0	9	Diesel	-
	Grader (Agg)	Motor Grader CAT 160M3 - 221 hp (14 ft width)	0	375	0	5	Diesel	-
	Bulldozer (Agg)	Dozer CAT D9T - 436 hp	0	754	0	9	Diesel	-
	Dump Truck (Agg)	Dump Truck CAT CT660 - 365-475 hp (15 cy)	0	1028	0	10	Diesel	-
	Compaction (Agg)	Vibratory Soil Compactor (tamping) CAT CP74B - 157 hp (7 ft width)	0	736	0	4	Diesel	-
Asphalt Paving - Recon	Paver	AC Paver CAT AS3301C - (26ft pave width, vibratory screed)	9063	1600	6	12	Diesel	68
	Tack Coat	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	250000	356400	1	4	Diesel	3
	Prime Coat	Emulsion Applicator (Prime, Tack and Seal) - 175 hp	250000	356400	1	4	Diesel	3
	Pneumatic Roller	Pneumatic Roller CAT CW34 - 133 hp (82 in)	13398	700	19	3	Diesel	65
							Total Gal=	**93,113**

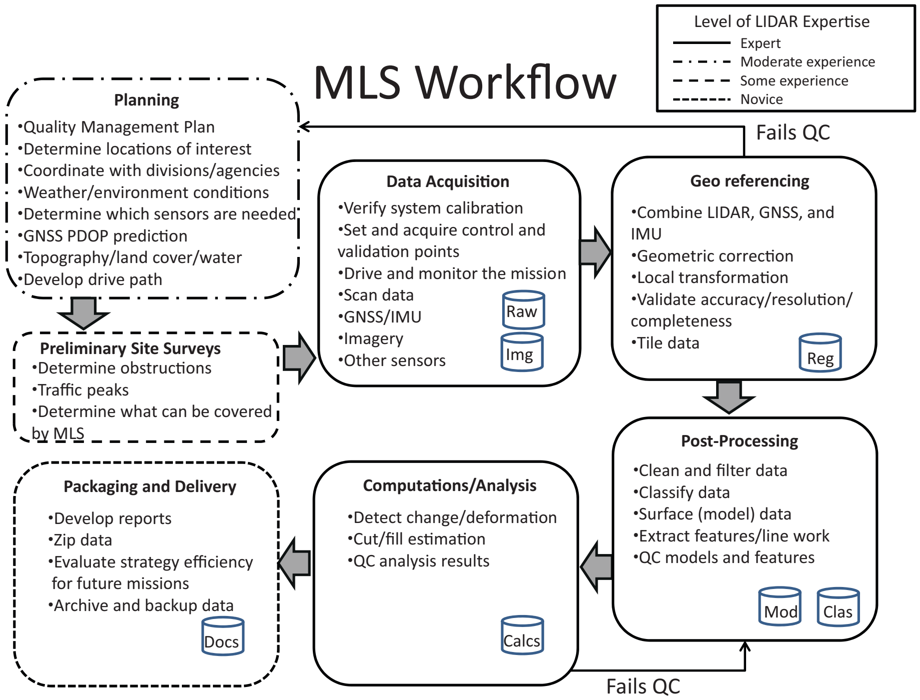

Figure 127 - Mobile LIDAR System Workflow – Detailed
(National Cooperative Highway Research Program, 2013a)

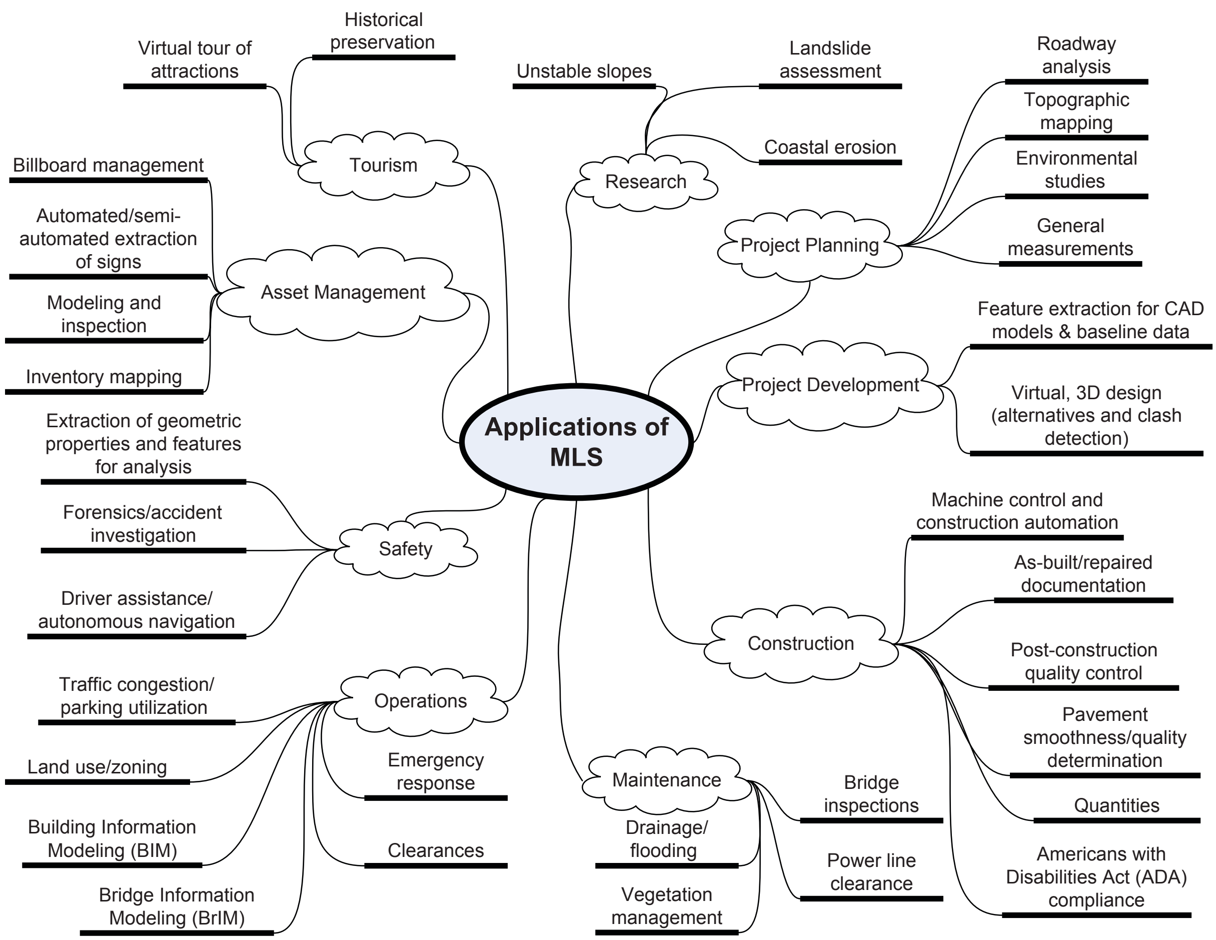

Figure 128 - Transportation Applications of LIDAR
(National Cooperative Highway Research Program, 2013a)